A Global Strategy for the Deployment of Humidification-Dehumidification Technology

by

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ABSTRACT

The world is suffering from a severe shortage of potable water. This effect is most noticeable in third-world regions, specifically in rural Africa and Asia. In these regions, clean water exhaustion has resulted in a myriad of negative affects such as diarrhea, infant death syndrome, hepatitis, and malaria. These sicknesses continue to take a serious economic and humanitarian toll on communities. By reducing the resources spent on these needless water related medical expenditures, clean water acts as an enabling good, alleviating poverty and increasing rural wellbeing. HDH technology, which has been compared against competing technologies in the field, has several advantages over other desalination technologies when providing this good to rural markets. While the installed material cost of HDH has been approximated to be about ten times greater than optimized competitors such as reverse osmosis, HDH has virtually no maintenance cost or complexity, it scales reliably to low generating capacities, and it uses abundant solar heat instead of often unavailable electrical sources. Furthermore, the detailed market analysis in this paper shows that there are clearly markets which are ripe for HDH adoption, specifically the district of South 24 Parganas in West Bengal. Finally, multiple successful case studies have been investigated to compose an implementation plan, through which millions of dollars in profit are realistically realizable. Overall, HDH technology has key advantages which should help it towards successful commercialization.

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1. Introduction

The purification of water is an ancient problem which dates back thousands of years. At that time, the absence of any knowledge of bacteria or viral infection made the goal of filtration simply to make water taste better. The earliest recorded use of water filtration is 2000 BC in ancient India. Various Sanskrit writings detail methods to purify water, amongst them boiling and silver metal insertion. Among numerous Greek accomplishments, Hippocrates began in 500 BC to purify water through sieves, removing the particulate matter. The advancements in purification technology then stagnated for a period of about 1500 years.

But in the 1600s the science in the field began to improve again. In 1627, Sir Francis Bacon attempted to use "heavier" sand to filter out the salt in ocean water. While this experiment was a notable failure, it nevertheless was the first step in the direction of desalination. In the late 1600s microscopes were designed to see the bacterial content of drinking water. This finding created a popular movement towards clean water for all, and in 1804 the first water treatment facility using slow sand filtration technology was built in Scotland. In 1854, chlorine was introduced to treat a cholera epidemic, and in 1890 rapid sand filtration with chlorine additives gained a surer footing in the United States after being linked to the decrease in the rate of waterborne illnesses. In 1974, the Safe Drinking Water Act was passed in the United States, ensuring the right to clean drinking water for all Americans, and much more recently, the United Nations released its ambitious Millennium Development Goals declaring access to clean water as a fundamental right of every person [36].

Access to potable water has moved societies. Thriving ancient areas, Egypt and the Indus Valley, were built on the confluence of rivers. Other cities such as Rome developed the world renowned aqueducts, a ingenious yet complex engineering solution to their water needs. In Mesopotamia, the Sumerians gained power when the rivers shifted towards them, leaving the rest of the regions people to either submit to their rule or die[31]. Presently, Ban Ki-moon, the UN Secretary General stated,

"...few people paid much attention to the arid regions of western Sudan. Not many noticed when fighting broke out between farmers and herders, after the rains failed and water became scarce. Today...More than 200,000 people have died."

Water is an invaluable resource. As global populations reach 7 Billion, and supplies remain relatively unchanged, the problem of relieving shortages of water has only become more acute and time sensitive. Understanding one method to effectively meet the increased demand through a decentralized increase of supply is the subject of this thesis.

1.1 Document Information

This paper sets out to provide a roadmap for adoption of the Lienhard group's desalination technology on a worldwide commercial level.

1.1.1 Central Questions

As part of an emerging field, the technology studied naturally requires many questions to be answered. The process of purifying salt water to produce pure water is known as desalination. There are several large scale technologies which have already been widely commercialized to achieve this goal. However, small scale desalination options for rural areas that lack monetary or electrical resources are sparse.

Through years of research and development, new methods have been established to improve the efficiency and lower the cost of decentralized systems for small scale rural desalination. These new methods have the potential to revolutionize the way in which the rural third-world creates and consumes their water resources.

But there is currently a void of marketing information for this desalination sector. No target markets have been defined, no price points have been set, and no deployment strategies developed. Furthermore, an understanding of the needs of the end customer, as well as the governments and water distribution intermediaries involved, has yet to be laid out [34].

Without this critical business information, investment in this technology will be stalled indefinitely. Consequently, there is a pressing demand for answers to these fundamental issues before further progress can be made.

1.1.2 Document Sections

The document is split into five main sections detailing an implementation plan for humidification dehumidification desalination technology on the global scale. First, the remainder of this introductory section details the extent to which water is becoming a global issue, and the necessity of desalination to be one of several solutions. The thesis then moves on to the specific forms of desalination which have either been widely adopted in the market today, or which are on the path to future commercialization. The third section of the document is dedicated to the Lienhard group's humidification dehumidification technology, with a full explanation of its costs and features. Target markets for the technology are then identified through a careful analysis of resources and local competitors. Finally, an implementation plan for the Lienhard group's technology is laid out.

1.1.3 Interplay Between Technology, Market, and Implementation

This document is a static collection of information. Once published, this paper does not vary its recommendations or timelines based on current events, pricing changes, or technology leaps. Therefore, the recommendations of this paper are not indented to be read as broad, time-irreverent statements on the methods for success of the product; rather, this paper is hopefully an effective guide for contemplating the problems which must be solved before success is possible, and for laying the framework for the business environment in which this product sits.

Furthermore, as things change in the sectors of technology, market, and implementation, the recommendations of this document must be revised to fit the current landscape. It may very well turn out that in the planned implementation of the idea, new factors in the market and technology are discovered, altering the entire nature of this paper's other conclusions. For example, certain case studies have shown that even simple improvements, such as moving the water supply closer to the village center, can actually destroy the social fabric of a village. In this specific case, the villagers previously socialized on the long walks to the water tank, but this pretext for communication was undone by the now shorter walk to the well. Such negative changes in the social structure are largely unpredictable without actual implementation in the village. These unpredictable outcomes in the implementation could lead to a change in how markets are selected, or which technology to use. In this way, technology, market, and implementation are interwoven in a tight web, and changing one invariably leads to changes in the others.

However, these constant changes should not render this paper irrelevant. Just as a physicist can only calculate where a particle will end up if she knows its current position, this paper intends to give the product a current position in the market so that future positions will be easier to navigate and move into.

1.2 Water Shortage and Associated Problems

Water is a basic necessity of every creature on earth. ***Clean*** water, however, makes a much bigger difference. In independent laboratory studies, the consumption of clean water has been shown to prevent the contraction of illnesses as varied as stomach worms to cancer. These illnesses not only take a toll on the individuals involved, but consume valuable resources from their often cash strapped families and governments [40].

The problem of obtaining clean water is pressing. Across the globe, 2.6 Billion people do not currently have access to clean water for personal sanitation. This includes the ability to take a bath, properly wash ones hands, or even use a bathroom free from disease. Possibly more urgent still, 1 Billion of these people do not have access to clean drinking water whatsoever [3].
The signs of crisis are everywhere. Diseases such as diarrhea, cholera, and hepatitis run rampant, claiming the life of a child every 30 seconds[1]. Contaminated water is responsible for over half of the cases of children underweight [40]. Even more seriously, in regions such as Bhopal, India, where water contamination has become hypercritical, infant death has increased two-fold, while the incidence of stillborn babies has tripled[38]. Four percent of the world’s diseases and 5 million deaths in 2003 were directly related to the consumption or use of contaminated water [37].

Economically, in South East Asia, the UN 2009 Water in a Changing World briefing reports,

> *"Cambodia, Indonesia, the Philippines and Viet Nam lose an estimated $9 billion a year because of poor sanitation (based on 2005 prices), or approximately 2% of their combined GDP."*

The New York Times reports that a 2010 drought in China has affected over 90% of the country's wheat production, and has been a major trigger for rising prices around the globe. This rise in prices has been widely recognized as one of the contributing factors to the downfall of the Arab economies, and thus the 2011 revolts in much of the Arab world [43].

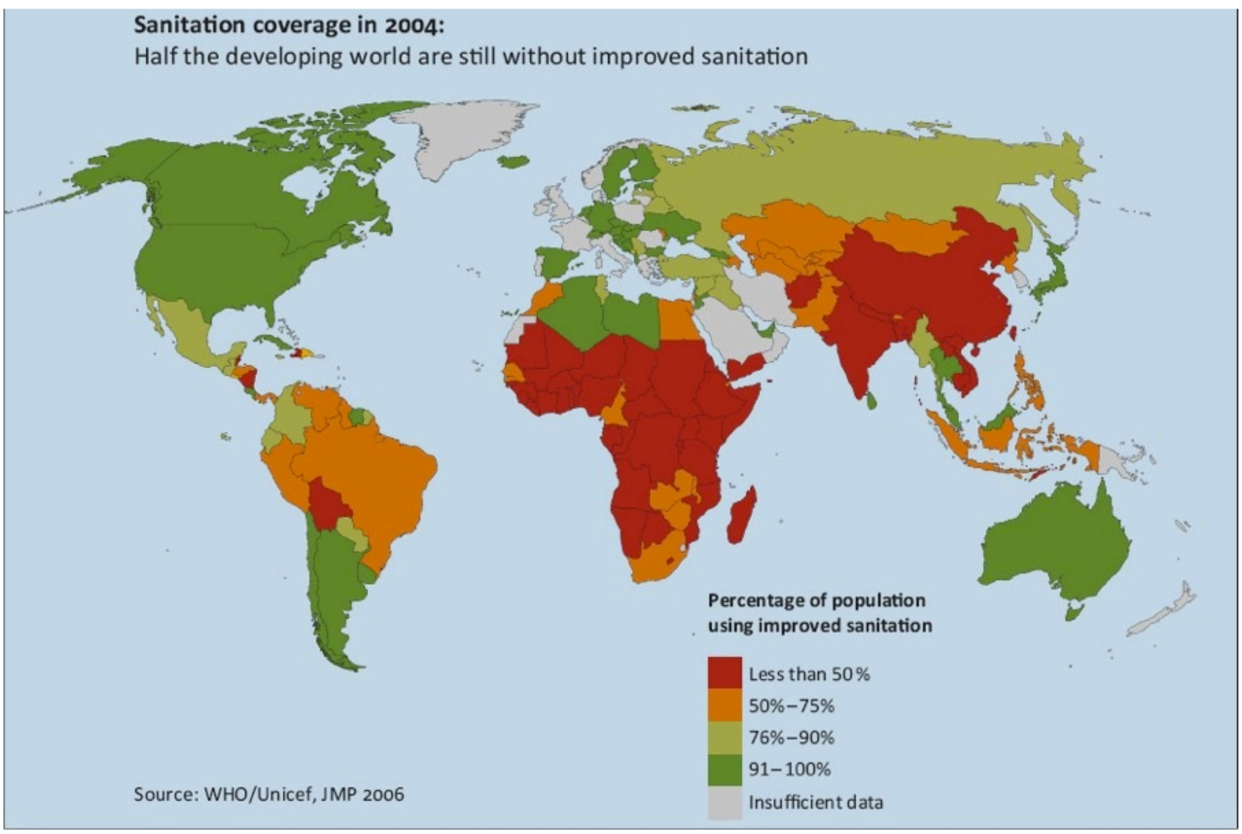

Figure 1- There is a significant portion of the third-world which lacks access to clean water. Much of China, India, and Africa are without drinkable supplies. These areas are consequently suffering from high levels of water related illnesses and death. [6]

While water contamination issues may be limited mostly to the third-world, America and its industrialized colleagues will have to work to avoid the impending shortage of fresh water as well. Two thirds of the United States is predicted to run short on clean water in the next three years. In 2010, Arizona and New Mexico used over 1 Million m^3 of non-replenishable water per day, while lake Mead, a source of 90% of the water for Las Vegas, is beginning to run dry [41]. Worst of all, America is addicted to water. Among first world countries, the United States leads the pack in per capita water use, consuming an astounding average of 600L daily per capita (note that this figure includes all water use other than power plant cooling, such as hygiene, meat production, and agriculture).

And the third-world is predicted to catch up. With rising economic growth, countries such as China and India are likely to consume more water intensive goods such as meat and clothing. These countries are also large consumers of water hungry grains such as rice, and their increasing populations will demand more of these foods. This predicted rise in water consumption will absolutely cripple the current system. However, even at current usage rates, the supply of water is running out.

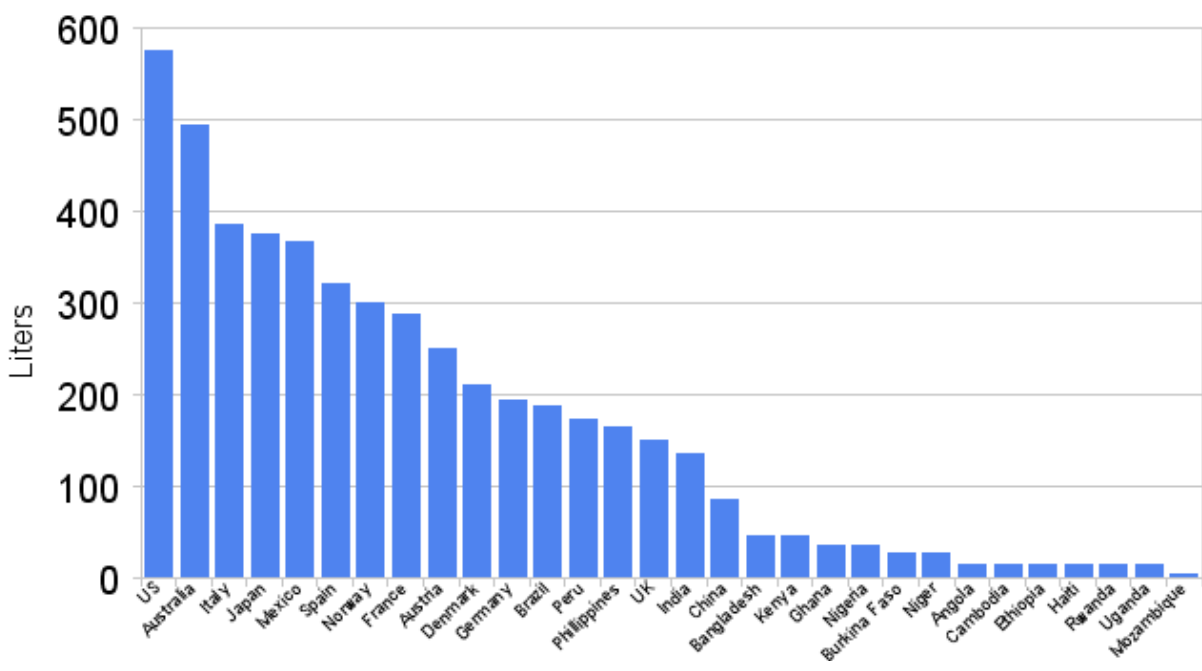

Figure 2- World water usage rates per capita. Individuals in the United States clearly consume the most water. As third-world countries such as India and China begin to catch up to the United States in living standard, and therefore consumption of water intensive goods such as meat and clothing, water use in these countries is projected to rise dramatically [42].

There is a potential solution. The past century has seen a great increase in the ability of technology to meet this increased demand through an increase in supply, by a process known as desalination.

1.3 Demand for Desalination

Desalination is the process of purifying salt water and making it potable. Over 70% of the earth is covered by water, but less than 1% of this water is both pure and recoverable. 97.5% of the water is in the oceans. Of the other 2.5% pure water, almost 70% of it is stuck in glaciers and un-tappable groundwater sources.

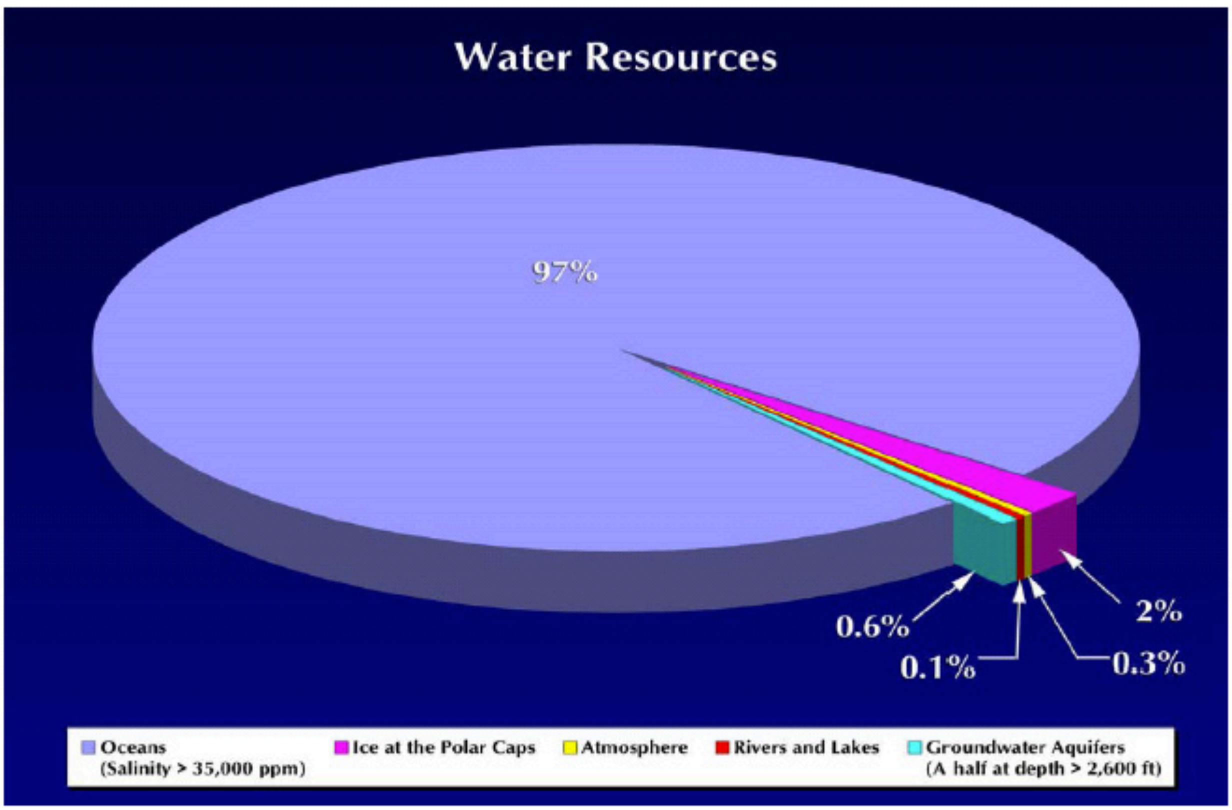

Figure 3- Less than 1% of the earths water is in a form that is readily drinkable [8]. If water usage rates stay as they are around the world, the replenishment rate of fresh water cannot meet the needs of the world's demand by itself. The supply must be increased using the largely untapped 97.5% saline ocean reserve.

The 1% that is present as useable water is being depleted. As noted in section 1.2, water is being consumed and polluted at a rate never before seen in human history. This trend is already starting to take its toll on the health and wealth of all people around the world, and the consumption rate of this water is projected to continue to rise.

The crisis has been deemed 'peak water' by some experts in the field. This intentional reference to the Hubert curve, which accurately predicted the peak in global oil supplies, is intended to demonstrate that water itself is an extinguishable resource. In order for a resource to be exhaustible, it must be nonrenewable at its rate of usage. Oil, for example, takes millions of years to form through the decomposition of bones under extreme pressure. Therefore, the current usage rates of oil clearly exceed the rate at which new oil is made, making the use of the oil resources today nonrenewable.

In this way, water use can be characterized as either renewable or non-renewable. Much of human water use today is renewable, and does not change the rate of recharge of the water supply. The use of river and lake water, if kept at a level at or below rainfall and glacial melt rates, is renewable and can continue indefinitely. The most common non-renewable use of water is from groundwater aquifers. These aquifers fill slowly, and are being used up rapidly around the world. India, the US, and parts of Southern China have seen their groundwater supplies decrease drastically in the past 30 years, creating severe pressures on their water system and leaving many farmers without a consistent means to provide water to their crops. Moreover, much of the water used from these aquifers finally runs into the sea, making its use in the future impossible [42]. The depletion of nonrenewable stocks makes the supply of water a decreasing quantity. Without a corresponding increase in supply by tapping currently unused water resources, the demand for water will quickly outpace its supply.

This requires an increase in utilization, through desalination, of the 97.5% of water left in the pie. According to Global Water Intelligence, leaders in international water market analysis as of 2010 [2], *“Spending on desalination projects will increase to $3.3 billion per year by 2016, representing an increase of 191% over today's spending.”*

Clearly, the field of desalination is taking off, with many different technology options to choose from. Given the demand for desalination, deciding between these technologies is now a much more exigent consideration.

2. Technology Landscape

There are several different methods on the market today which remove salt from water. Each of these methods is detailed and compared in this section. In the course of this technology review, it will become clear that some methods are much better suited to preform under certain conditions, while other methods are much more adaptable to a range of environments, but are often less efficient. These tradeoffs are the seeds of future target market analysis, but are also promising for the desalination market as a whole.

2.1 Desalination Basics

The dissolution of salt in water is an energetically favorable process. Thus, all desalination processes must input some form of energy into saline water in order to separate the salt from the pure water. This has led to several measures of performance which are used in the literature to compare the various desalination methods. These metrics are discussed below.

The Gained-Output-Ratio (GOR), is a measure of the amount of fresh water produced to the heat input to the system. Higher values of GOR are favorable because they signify lower energy use for the same quantity of distillate[17].

However, GOR values must be compared carefully. A direct comparison of a GOR value for a process which consumes electrical energy to one which consumes solar energy may incorrectly assess the benefits of the electrical system over the other. If a paramount concern is power-plant generated electricity use, than even very small GOR values are acceptable if these values represent the use of only renewable or waste heat resources. Therefore, a GOR value should be understood only as a measure of the efficiency of a isolated desalination process, and not as a comparison between the efficiency values of various processes.

If the actual total overall energy required for electric desalination processes was desired, one must account for the total energy of the entire process or the 'well-to-wheels' power use total. For instance, desalination plants using coal generated power should actually take into account the power use for mining the coal, transportation of the fuel, processing and generation costs, electrical wiring costs, and finally the efficiency of the desalination plant itself. If the efficiency of the power plants is further taken into account, the new full cycle efficiency of the electrical desalination process will reduce even more drastically. Given that tracing the source power for each process would consume entire theses in and of themselves, the GOR values in this paper will only be used as a comparison tool for processes which use similar types of energy.

Energy use per Kg water (kJ/Kg) is simply another measure of the amount of energy that must be input into the system per unit mass distillate. Lower kJ/Kg values are desirable, but as discussed above, systems using electric power will tend to have lower energy values but cannot be compared on face to thermal values due to the unaccounted for efficiency losses in the power generation life cycle.

Finally, the salinity of water can be broken down by varying levels of salt concentration. Brackish water has a higher salinity content than pure water, but has less salt particles than seawater solution. Brackish water is generally produced by industrial pollution of groundwater sources, or in areas where fresh water and seawater meet, and has concentrations less than 30 parts per thousand (ppt). Seawater has a salt concentration above 30 ppt, but below that of brine. Finally, brine, which is the concentrated discharge of a desalination system, has above 50 ppt salt.

2.2 Current Technology and its Limitations

There is an energy minimum to separate salt from water. By considering the entropy change qualitatively, one can deduce why this minimum must exist. Entropy energetically favors disorder. As salt is removed from a portion of the liquid, the order of this portion of the system is increased, which entropy dictates must cost energy. Therefore, the process of separating salt from seawater is theoretically bound to a minimum energy of approximately 3kJ/kg[12]. This minimum energy has been found to increase with the amount of salt removed from solution, a simple extension of the argument that in order to create further separation and reduction of system entropy, even more energy must be used.

There are other real world limitations to the efficiency of a desalination system. The salt water feed must be pumped to the facility from the source in order to undergo a desalination process. The energy required for this pumping will vary, however, it does increase the theoretical minimum energy for the complete process, and at least requires consideration when deciding where to locate desalination plants. Plants located at higher elevations and pumping water from sea level will incur energetically costly pumping, and should take this into consideration when comparing desalination of the seawater against other options like grey water purification.

Thermal distillation and membrane processes are the two major sectors of desalination technology. The technology described below are the most mature, and have come the closest so far to achieving the theoretical limits. Other desalination methods exist, but they are not as promising or widespread, and have been omitted for this reason from this paper.

2.3 Thermal Processes

Thermal distillation processes use heat and pressure difference to create water vapor from saline solutions. These processes are the oldest desalination methods on the market today, and are widely used across the Middle East. Thermal systems have been attractive desalination methods due to their simple design, centralized plants, potential use of waste heat or solar thermal energy, and low cost.

Thermal processes effectively uses the physical property that the boiling point of water is reduced due to a reduction in system pressure. On a molecular level, when there are fewer molecules "pushing" on the surface of a fluid due to a reduction in pressure, the fluid molecules require less energy to escape from the fluid and move into the vapor stage. Therefore, if a container is kept at a low pressure, than the heat source for the salt water can be weaker, and vapor will still be created. Vapors also have the important property that upon condensation, heat is released, known as the heat of condensation. Thus, simply on the change of state from vapor to liquid, water vapor releases a very large quantity of heat to the surrounding environment. Both Multi Effect Distillation and Multi-Stage flash are structured in ways which abuse both of these properties effectively.

2.3.1 Multi Effect Distillation

Multi Effect Distillation (MED) was the first desalination method to be used widely on a commercial level. MED is simply a combination of stages, ranging in both temperature and pressure. The saline input stage is maintained at the highest temperature and pressure, while each successive stage is maintained at both a lower temperature and pressure. The temperature gradient follows naturally, as will be seen shortly, from the way in which the stage is heated, while the pressure gradient is maintained so as to keep the level of vaporization relatively constant.

Salt water to be purified is passed into the first container, known as an effect, where the salt water is sprayed to coat the surface of a heated pipe. As the water flows down the sides of this pipe, it increases its thermal energy, and begins to enter the vapor phase. This newly created water vapor, which is slightly cooler than the input pipe temperature, is then passed to the next stage through another pipe where it is used as the heat source for this second stage. Once again, seawater is sprayed onto the surface of this second pipe in the second effect which is also at a lower pressure, is vaporized, and passed into the third pipe, and so on and so forth (fig. 4). In this way, MED has been made to be an extremely efficient thermal process, and typically has a GOR value around 15. MED also has the additional benefits of not requiring pre-filtration of the seawater feed, as well as a 24 hour throughput, and a low required operating temperature.

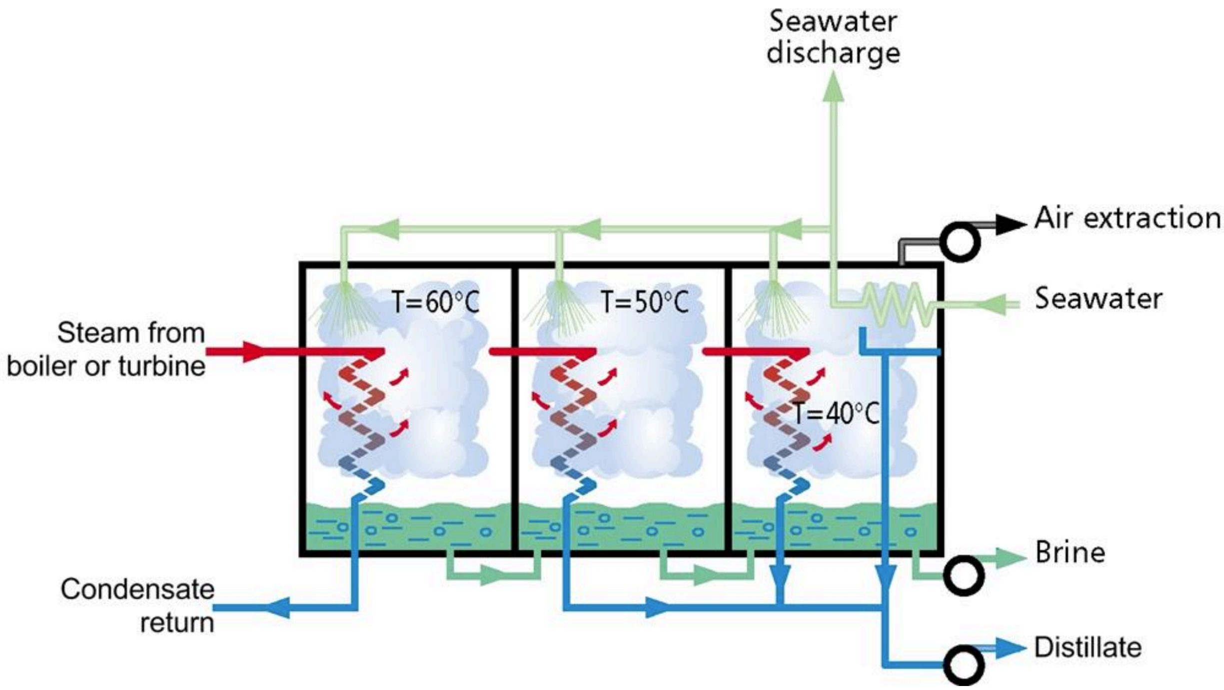

Figure 4 - Seawater enters the MED system on the left of this diagram. Heated steam is input into a pipe in this stage. This is the only external heat input into the system. After this point, the vapor produced in one stage is used in the next stage, and each successive stage is maintained at a lower pressure. Finally, purified distillate is taken from the condensate of each stage [50]. The use of the vapor stream to heat the next stage is an effective method of increasing the efficiency of thermal processes.

However, MED suffers from a major problem: scale formation. This fouling issue is due to water boiling on the metal pipe surfaces, which creates energetically favorable sites for salt precipitation in the chambers. These stable sites for scale are extremely hard to remove, making the system unusable after years of scale formation. This required maintenance has pushed the market towards Multi Stage Flash as the thermal desalination method of choice.

2.3.2 Multi Stage Flash

Multi Stage Flash is the solution to the fouling problem in Multi Effect Distillation as long as the system is kept below a certain temperature. Instead of heating the water to a boil at each successive stage, the water is drawn into a very low pressure environment where it spontaneously moves from the liquid to vapor phase. As there is little to no bubble formation on the surface of the metal, the presence of energetically favorable scale formation areas is removed, and the fouling problem greatly reduced. The safe temperature range to avoid fouling is generally regarded to be below 120^{o}C.

One of the major disadvantages is that flashing water is more energetically costly than simple boiling processes. The cost of reduction in scale formation is a reduction in the GOR from 15 to 8, with an energy use of approximately 300kJ/kg[11]. Even though the energy use is much higher, multistage flash is the predominant technology used worldwide, accounting for 40% of the world's desalination plants, and over 90% of thermal desalination in use[15]. This has been achieved through clever usage of waste heat from power plants, reducing the new energy input to these plants, making them economically feasible. This waste heat would be input at the same point as the heating steam(fig. 5). Heat is also recovered in every stage as the seawater and brine feed is used as the condensation step of the previous vapor phase. It is also clear from the figure that brine recycling is also present in many MSF designs. This reuses waste heat that has not ben used in the flashing of water, further increasing the overall efficiency of the system. Heated seawater is constantly added to this brine to dilute its salt content.

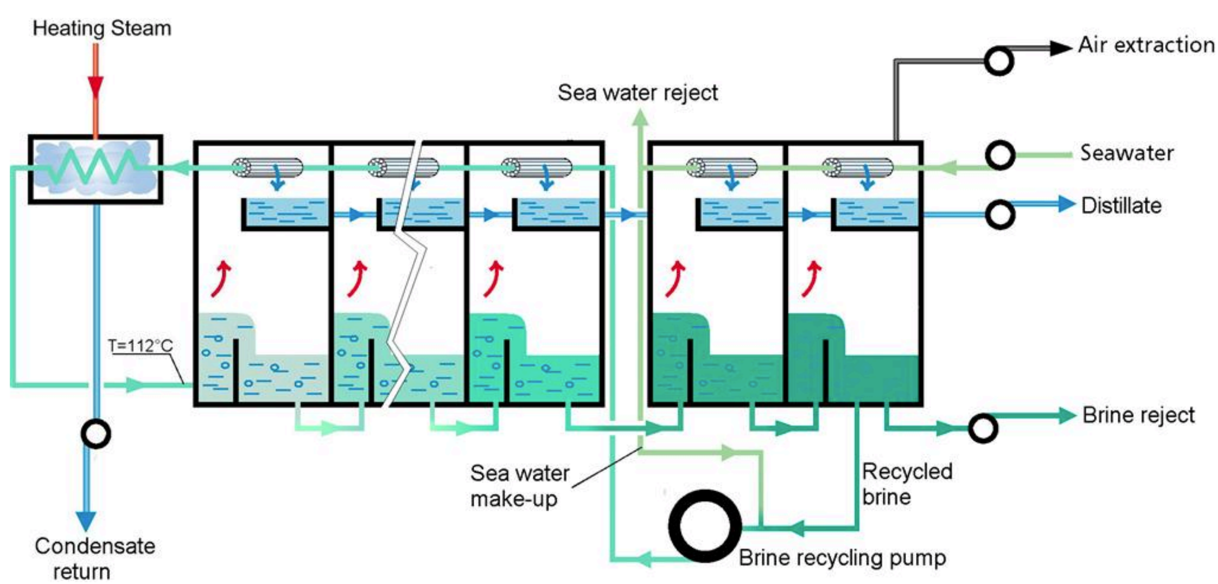

Figure 5 - Schematic of classic MSF plant. Note that the same efficiency gains of MED are captured here. The input feed water is heated by the condensation of the purified water vapor. Moreover, brine which still contains heat is reused. The MSF system, maintained at temperatures below 120 ^{o}C, avoids scale formation, but at the cost of about a 50% reduction in energy efficiency[51].

2.4 Membrane Processes

Membrane filtration processes are currently the other dominant form of desalination on the market. Membrane technology involves the segregation of salt water from a pure water solution by a porous film designed to allow only certain particles through. The two major membrane processes, Reverse Osmosis (RO) and Electrodialysis (ED), generally have higher GOR and lower kJ/Kg values than the thermal processes, but need steady supplies of electricity to operate. Both RO and ED plants have traditionally been designed to be centralized, large facilities as the efficiency for these processes increases with reduced saline concentration in the sea water feed. More specifically, for smaller desalination systems, the salt left over from filtration is not diluted by as large a supply of water, and the salt concentration is more significantly increased. This concentration increase kills the efficiency of membrane systems.

Newer membrane technologies, such as Forward Osmosis, are working to lower the energy required and reduce the size requirements. As such, Forward Osmosis is also reviewed below, but is not currently a commercial success and should be revisited should it make serious strides in the space.

2.4.1 Reverse Osmosis

Reverse osmosis involves running the energetically favorable process of osmosis backwards. Natural osmosis is a process that occurs when two fluids of different concentration are separated by a semi-permeable membrane. The membrane, which is designed to only let the fluid and not particulate matter through, will begin to see the purer fluid move through it into the more contaminated liquid. Essentially, nature is attempting to equalize the two fluid concentrations. In the case of salt water separated from pure water by a semi-permeable membrane, the pure water will naturally flow into the salt water, as if there is a pressure pushing it in that direction. This "force" is known as the osmotic pressure.

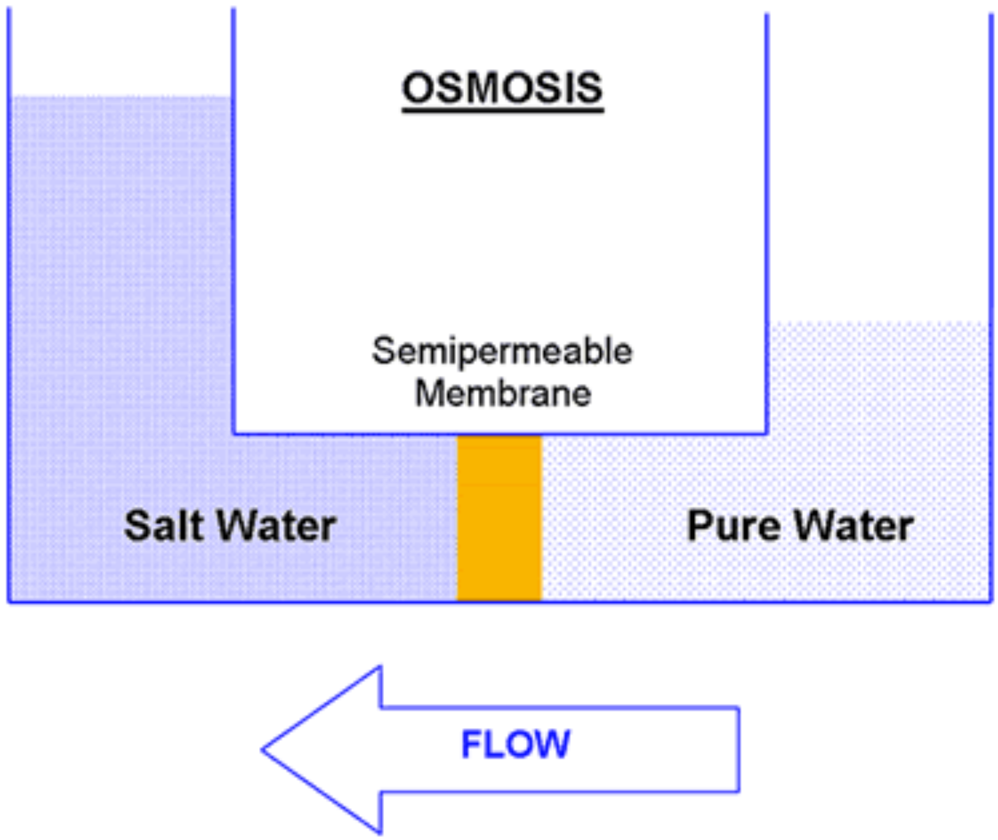

Figure 6 - The natural process of osmosis moves fresh water into salt water. The semipermeable membrane has pores not big enough to allow salt molecules through, but does allow water. Therefore, the side containing pure water statistically pushes more water to the other side than the salt water. The system will finally equilibrate when the salt water level increases to a certain "osmotic" pressure [52].

The reverse osmosis process works to change this natural fluid direction. In the salt-water fresh-water example, by applying a real pressure which is greater than the osmotic pressure to the salt water solution, water will actually flow out of the salt water and into the fresh water bath. This reverse of the direction of natural flow actually creates particulate free water.

The modern day manifestation of the Reverse Osmosis system is in a rolled sheet form. The feed solution is pumped at a pressure greater than the osmotic pressure through multiple feed channels. These channels are surrounded by semipermeable membranes, which are in contact with channels dedicated to purified water. The purified water streams are then combined to form a permeate stream, and released from the center of the cylinder. The brine, or left over salt water solution from the unfiltered input feed, is then output from the outside of the cylinder. In this way, many cells can be made in parallel and wrapped into a contained structure.

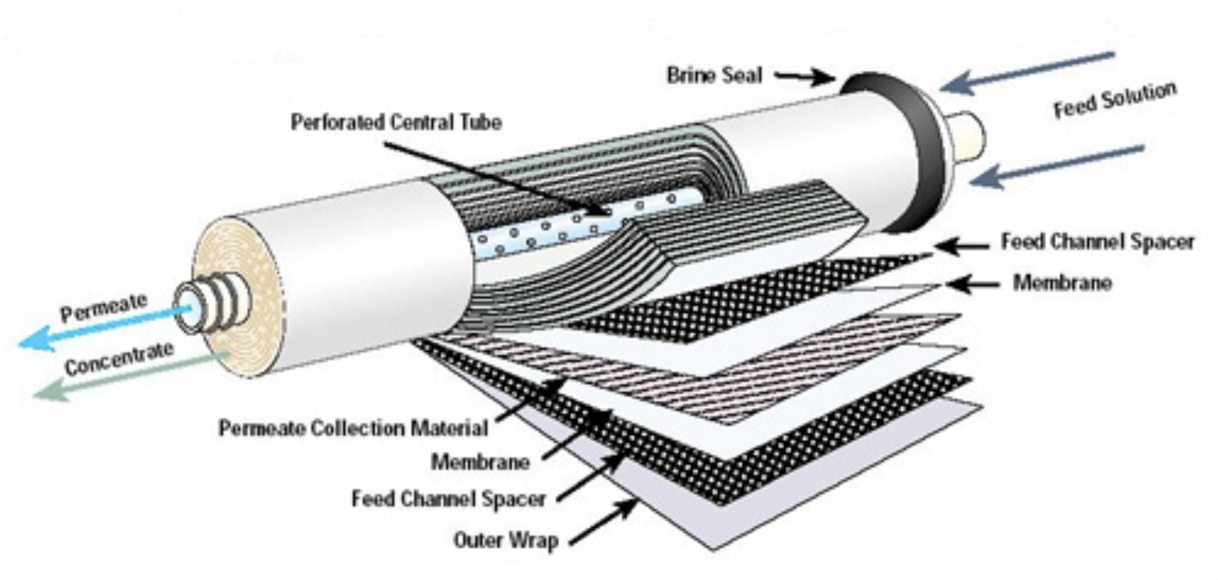

Figure 7 - A traditional manifestation of a Reverse Osmosis system is the tube shaped stacking shown above. The feed solution is passed on the right side of the cylinder at a pressure greater than the osmotic pressure necessary. The feed solution is thus pressed through the adjacent membranes, and is moved towards the center of the cylinder. The pure water and brine are ejected on the left [53].

Energetically, Reverse Osmosis is the most robustly engineered system, ranging in energy costs from 20-60 kJ/Kg to desalinate seawater, a 5-15x improvement over thermal distillation systems [11]. Note that as discussed earlier, this energy value should be considered a rough comparison of efficiencies just of the desalination process, and not of the overall energy process.

Reverse Osmosis does require pretreatment of the feed water due to film sensitivity to acids and large particulate matter, which does reduce the energy efficiency further. Even with this pretreatment, membrane fouling is still a major problem. As time wears on and more contaminated water is processed, small particulate matter will begin to get stuck permanently in the membrane sheet pores. This reduces the amount of water that can be processed, and also increases the applied pressure necessary to drive the system. Membrane fouling is devastating because of its long term affects. Even with cleaning of the membrane layers, long term pore clogging is often due to extremely tiny impurities, and is somewhat nonreversible. This can result in reduced membrane efficiency for the life of the system.

2.4.2 Electro-Dialysis Reversal

The process of electrodialysis works by utilizing membranes designed to reject particles of certain polarizations. Positive ion rejection membranes are alternated with negative ion rejection membranes. The salt water is then flowed through the system between these membranes, and a voltage is applied to the entire system. Negative and positive ions are pulled in opposite directions by this voltage, creating channels of high saline concentration and low concentration channels, or clean water channels.

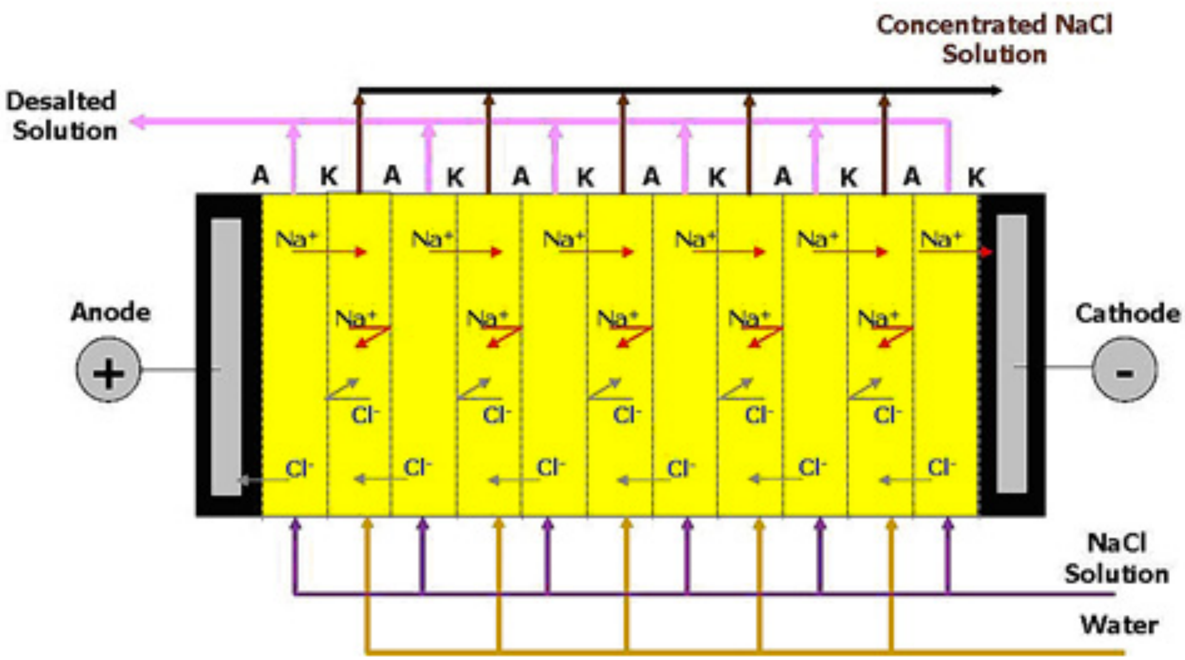

Figure 8 - NaCl dissociates almost completely in water. This leaves positive Na and negative Cl particles moving around freely in the solution. Electrodialysis Reversal isolates both of these particles into the same slots by pulling the positive ions one direction, and the negative ions in the other. This concentrates the salt, and purifies the water in every alternate slot. The additional ingenuity of this process is in the switching of the polarities of the power source. This prevents ion buildup in the membranes, reducing membrane fouling [54]. This process is more energetically costly than RO, and is generally not appropriate for salt concentrations above that of brackish water (<30ppt).

In order to avoid fouling problems, the voltage on the system is periodically switched. This reduces pore clogging by attracting particles stuck in the membranes out of their positions. Thus electro-dialysis reversal solves many of the fouling problems of RO [20].

However, electro-dialysis is more energetically costly than RO due to the nature of the voltage that must be applied, and thus is ineffective for purifying high salt-content seawater. Lower salt concentration solutions like brackish water can undergo this treatment effectively.

2.4.3 Forward Osmosis (FO)

Forward osmosis uses osmotic pressure to its advantage. In traditional osmosis, water naturally moves from the solution with a lower salt concentration to the solution with a higher salt concentration. In forward osmosis, a "draw" solution is used opposite the seawater solution. This draw solution is not composed of NaCl dissolved in water, but rather a much more concentrated salt solution than the salt water it opposes. For example, salt concentration in seawater is approximately 35 parts per thousand, whereas the draw solution might use NH_3/CO_2 dissolved in water with a concentration of 50 ppt or higher. When the proper semi-permeable membrane is placed between these two solutions, water from the NaCl seawater solution moves into the draw solution naturally.

Once the water moves into the draw solution, it must be removed to get the product water. The pure water is extracted from the draw solution in a recovery chamber. This chamber is designed to heat the draw solution up to a temperature at which the draw salt vaporizes. Once the draw salt has completely vaporized from the solution, the product water can be extracted for use. The vaporized draw salt can then be recycled back into the original draw solution, to begin the process again.

There are several challenges remaining for the FO system before it is fully deployable. The draw salt must be carefully composed in a manner that allows it to be evaporated off at a relatively low temperature (<100 ^{o}C). The membrane must not allow for either salt, NaCl or the draw salt, to pass through, and the draw salt cannot be toxic or destructive to the membrane. Finally, the draw salt must have an extremely high solubility in water so that it does not precipitate out [77]. Forward Osmosis is a process which could save a tremendous amount of energy once the technology has overcome the hurdles described. It has been projected that:

> *"Energy savings of FO compared to current technologies, on an equivalent work basis, are projected to range from 72% to 85%[19]."*

Moreover, FO is projected to have far fewer problems with fouling of the membrane, as the pressure with which the water pushes against the membrane need not be as high as with RO systems. Due to this reduction in pressure against the membrane, less particles get stuck, and the membrane is thought to last longer [78].

Forward Osmosis, although promising, is still in its nascent stages and may face unforeseen challenges in the future. FO is also currently a relatively expensive technology due to the complex composition of the draw salt, and the lack of economies of scale. It is too soon to tell if Forward Osmosis will become a major player in the world market in the years to come.

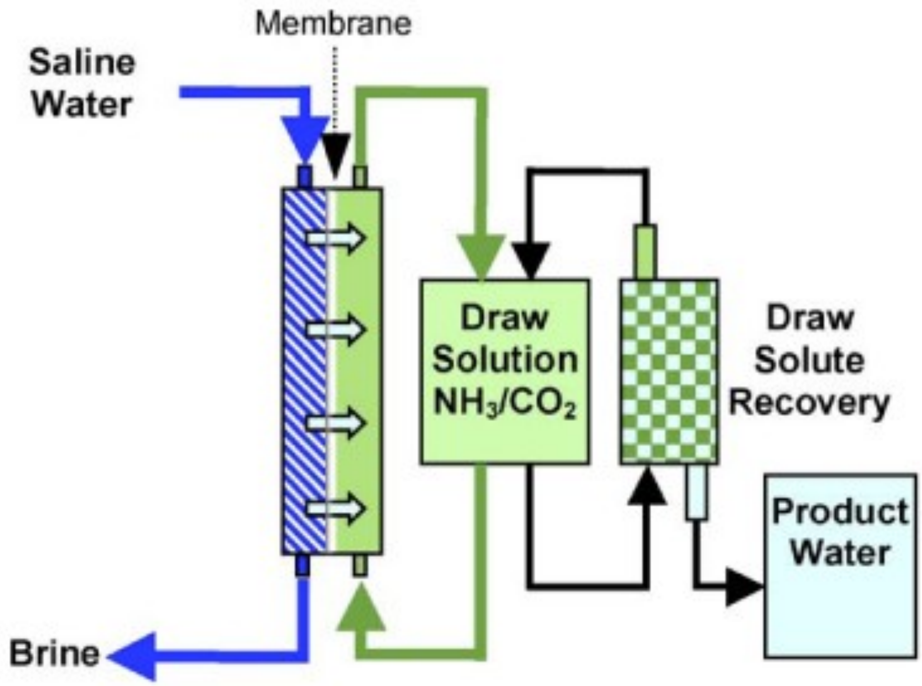

Figure 9 - The forward osmosis system uses a draw solution which has a higher concentration of particulate matter than the saline water feed. The water from the saline feed naturally moves into the more concentrated draw solution by the process of osmosis. The draw solution is then moved into the recovery stage, where the draw solution is heated to a temperature where the draw salt is evaporated off and then moved back into the draw solution. Once the draw salt has been removed from the water, the product water can be extracted for use. Forward osmosis can utilize waste heat from power plants to evaporate the salt from the recovery stage, making it even more efficient [77].

2.5 Market Need

Even this large number of desalination technologies fails to saturate every market need. Almost every technology discussed is best suited for a centralized production model, where waste heat or large quantities of electrical energy must be used to desalinate the water. Moreover, the technologies discussed are often too expensive to build and operate, hitting a price point which makes these technologies prohibitively costly for rural people to buy.

As will be described in much greater detail in the Market section of this paper, there is a need which exists for rural people who currently do not have access to clean water. These villagers do not have high income levels or electricity available to them, but they often have access to sunlight and saline water free of charge. A system which is able to take advantage of these available resources, while not needing the others, is the Lienhard group's Humidification Dehumidification system as described below.

3. Humidification Dehumidification

The Humidification Dehumidification (HDH) process is in a prime position to enter the desalination marketplace to address the needs of small scale rural populations. The system can be engineered to run entirely on readily available solar thermal energy, its performance is not based on the salinity of the input water feed, and it is extremely simple to repair, a crucial factor for uneducated village populations. These advantages make HDH an attractive prospect for rural communities in need of cost-effective solutions. The Lienhard group at the Massachusetts Institute of Technology has engineered this system to reduce the natural inefficiencies and maximize the amount of water purified.

3.1 Humdification Dehumidification Basics

The basics of HDH are very simple. At its core, an HDH desalination system mirrors the natural rain cycle. In the rain cycle (fig. 10), the sun strikes the surface of the oceans, increasing the water's energy. As the water molecules heat up, they begin to vibrate more rapidly due to the increase in their kinetic energy. This increased vibrational energy increases their opportunities to escape the surface energy of the liquid, and consequently increases their odds of moving into the vapor phase. The particles in the water do not experience this vaporization. Salt, as well as the other particulate matter in the water, is left behind in the process of moving water into the pure vapor stage, producing water vapor which is free from any salt content.

Once in the vapor phase, this salt-free water vapor is then condensed, forming clouds. These clouds thicken, eventually precipitating out as rain. Finally, this rain is collected and stored for future use in lakes [33]. The miniaturization and optimization of this process is the Humidification Dehumidification system.

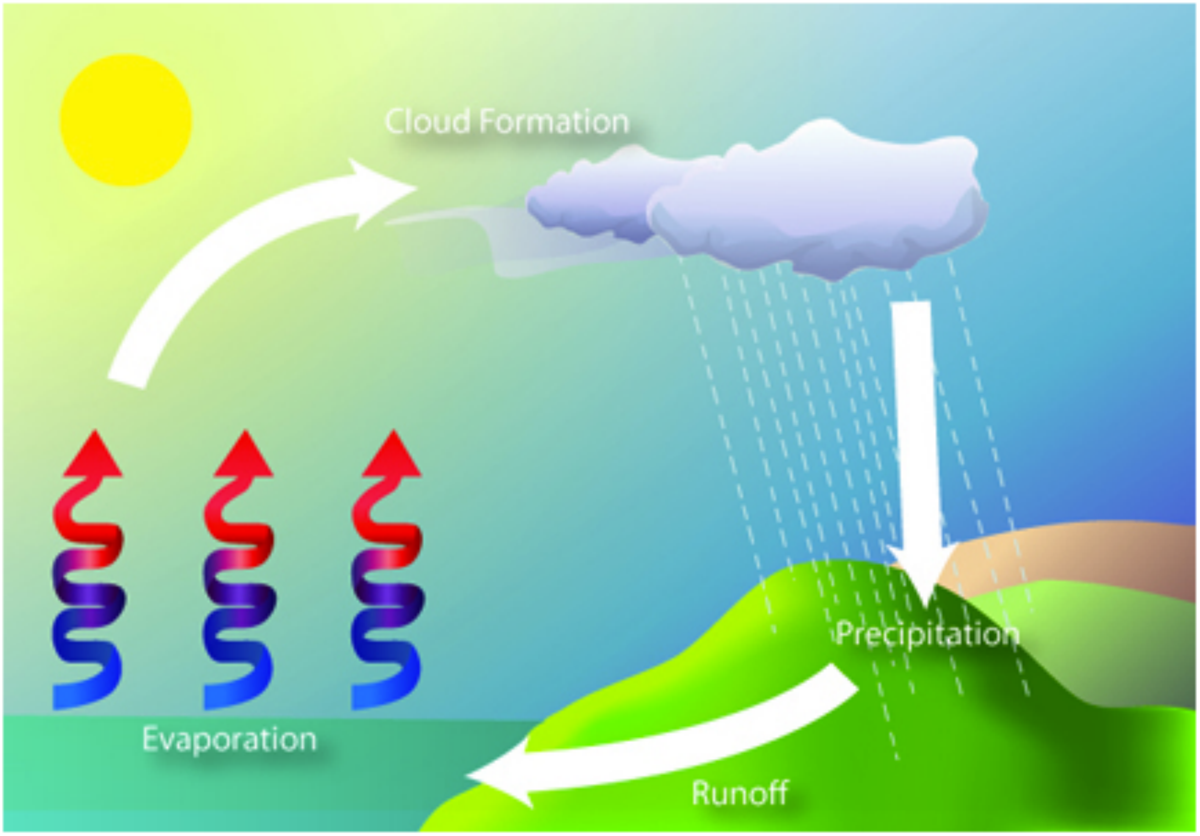

Figure 10 - The natural rain cycle is a model for the Humidification Dehumidification desalination process. The natural cycle does suffer from several inefficiencies, which the Lienhard group's technology fixes.

An HDH process improves on this cycle by separating each process and optimizing them individually. In the humidification stage, HDH increases the surface area of the water to maximize the efficiency of the process. HDH uses waste heat and effective thermal traps to capture more solar thermal energy. Finally, in the condensation step, HDH reuses the heat released when the vapor phase turns back to liquid. Even with these optimizations, HDH systems have been extremely inefficient energetically in the past, with GOR values typically around 1 [18].

3.1.1 Optimization of Humidification

HDH systems use packed beds to improve the efficiency of air humidification. A packed bed is composed of a fill which increases the surface area of the heated salt water, increasing the rate of evaporation. As water is pumped from the nozzles it coats the surface of the filler material placed in the packed bed. Air is then made to pass through the fill. The air, after passing through the warmer water in the fill, begins to expand and thus increases its humidification limit. As moisture begins to fill the air due to this increase, salt is left behind in the packed bed and pure water is moved into the air.

The structure of filler material is a crucial one that effects the transfer of moisture to the air. Filler materials can either be placed purposefully in a grid in the packed bed, or randomly positioned. Purposeful positioning is achieved through the use of film fills, or corrugated sheets of metal stacked in columns. These stacked fills tend to have a higher surface area than the random packing fills and thus increase the efficiency of heat transfer and air humidification. However, these metal sheets are prone to fouling problems, and require a more heavily treated salt water feed. Random placement of a fill requires less precise assembly often reducing overall costs. These fills do decrease the thermal performance by a factor of 50% due to the reduction in surface area and the increase in the overall pressure drop of the air stream [32]. The increased pressure drop requires a higher air speed into the packed bed which requires either greater fan speed or increased natural circulation. These tradeoffs will be addressed when looking at the costs of materials and the production capabilities present in each target market.

3.1.2 Optimization of Heating

The solar heater is another point of optimization for the HDH system. The system can either be designed to heat water or to heat the air stream. Air heated systems have traditionally been discouraged due to the inherent losses in the heater design. An air heated system heats up the air which subsequently enters the humidifier and absorbs water vapor. However, the heat lost to the water which does not increase vaporization is simply lost to the water phase, and is never efficiently reused. In the case of the solar *water* heater, the water is heated and then passed into the humidifier. Some heat that is lost to the air is eventually passed back into the incoming seawater feed on the condensation step. Due to this, solar heating of water is generally used as long as optimization of the condensation step is also carefully managed.

3.1.3 Optimization of Condensation

In an HDH cycle, condensation is made to occur by utilizing the temperature gradient with the incoming saline feed. When the hot humidified air precipitates out on the pipes carrying the relatively cold salt water entering, it releases its heat into the salt water solution. In this way, the thermal energy of condensation is not lost to the atmosphere as in the rain cycle, but is deposited back into the salt water so that less thermal energy needs to be used in the future. The choice of materials and shape of the transfer surface for the specific HDH system used is detailed in 3.2.

3.1.4 HDH System Categorization

There are two categories of HDH systems: Closed Air, Open Water (CAOW) and Closed Water, Open Air (CWOA). The CWOA system is typically not used, as it has been understudied in the literature. For the purposes of this paper, it will not be discussed further. Should developments in CWOA systems be appealing in the future, CWOA systems should not be disregarded simply because they have been passed over at the time of this papers writing.

The CAOW system is the same system used by the Lienhard group (fig. 11). As the name implies, this system takes in salt water from the ocean or brackish water source, and discharges fresh water for consumption and use. In this way, the water loop is open as water is continually refreshed and discharged. The air loop, on the other hand, is closed. The same air is always circulating through the system. This air is humidified with water vapor, moved to the condenser stage where the fresh water is pulled out of the air, and is then pushed back to be humidified again. In this way, the air acts as a carrying agent for water. Just as the same train takes different people from one station to another, the same air takes different water from one stage to another.

Studies on CAOW indicate that this type of system works well with both naturally circulating air and or with forced circulation. Naturally circulating air can show the same performance statistics as forced circulation systems, but often suffers from slower circulation and thus lower throughput. If blowers need to be used to circulate the air, photovoltaic panels can be employed to reduce the need for external sources of electrical power. Regardless of how the air is circulated, the water flow rate of the system must be carefully controlled to optimize the process [18]. This water pumping system can also be run using photovoltaic panels as discussed shortly.

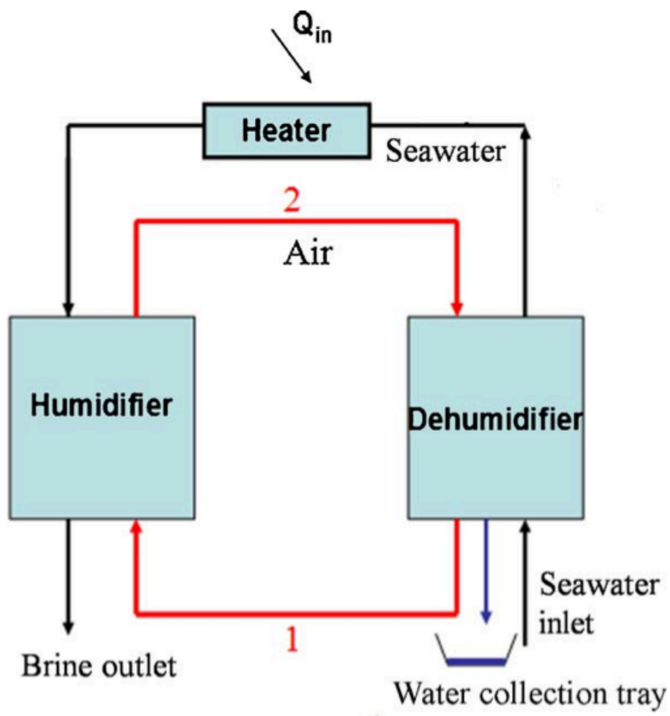

Figure 11 - Schematic of the Closed Air Open Water system used by the Lienhard group. The air which is circulated first humidifies, then deposits its water onto the incoming salt water pipe, then moves back to be humidified again. In this way new air is never required. Both the water which is purified and the brine are open in that they are pumped out of the system.

3.2 Lienhard Group Technology

The Lienhard group's technology is a version of water heated CAOW Humidification Dehumidification. The potential output of the system varies based on the size of the box, but can reach values anywhere from .01m^3/day (10 L/day) to 1m^3/day (1,000 L/day). Per capita ingested water consumption is far less than total per capita consumption of water for all purposes, with ingested water per capita sitting at approximately 3L/day in third world countries [80]. As the HDH system is quite small and not indented to be used for agricultural needs, the HDH technology is meant to satisfy this 3L per capita ingestible water need. At this lower rate of intake, the average HDH box described could provide clean water to about 3 to 300 people depending on the daily capacity of the system. The sizes of the system components can vary to meet changes in this daily production capacity as demanded.

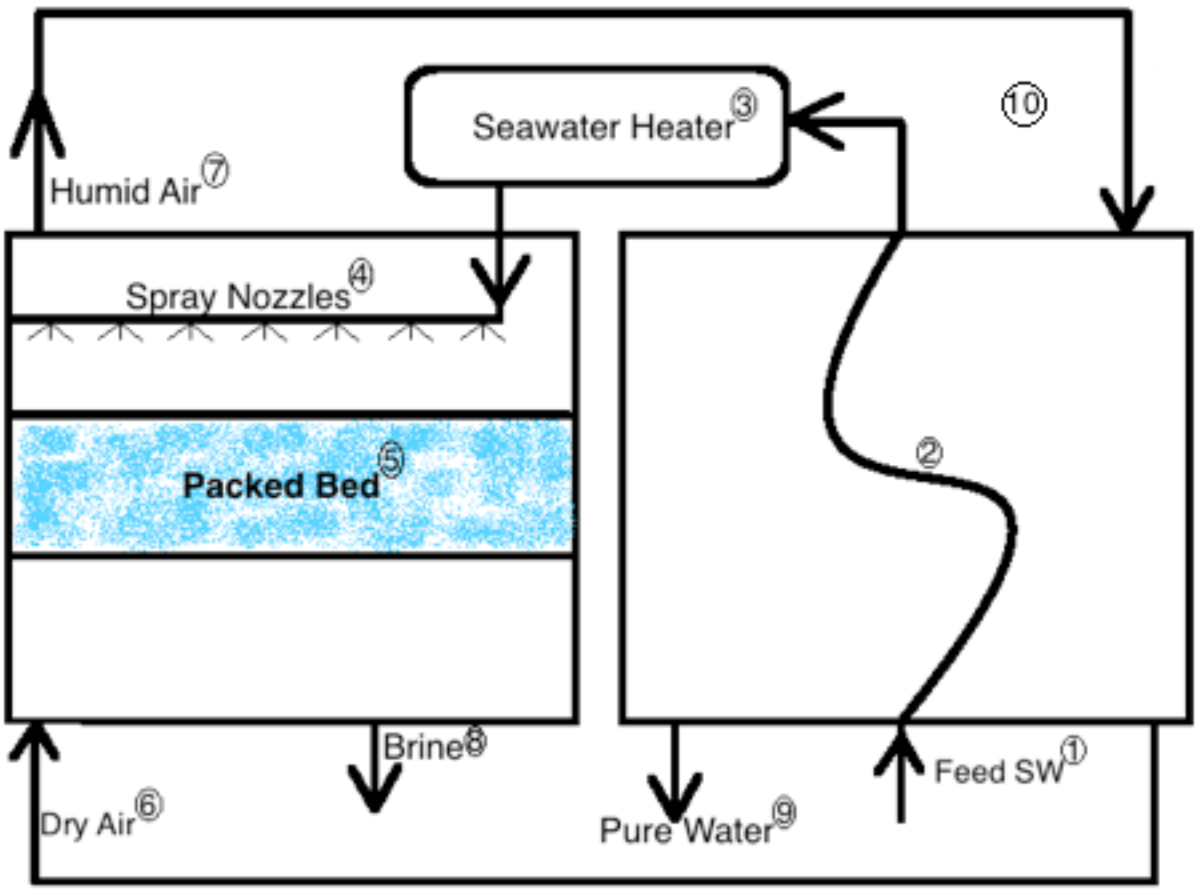

Figure 12 - Components of the Closed Air Open Water system are labeled above. Each of these parts is described in further detail below. The operation of the system is generally as described in the sections on optimization above.

3.2.1 Schematic Description

The parts labeled (fig. 12) are described below in numerical order, with the necessary depth to size and price the materials for the product. As the full system has yet to be completely designed, materials for certain parts are not yet set. The descriptions are meant to be a guideline for the functionality of the parts, more than of the specific material which will fill this need.

(1) This is the intake valve for water into the system. The intake valve is designed to receive feeds from both commercial vendors of water and from local brackish water feeds. The input water pressure is controlled at this point by a low flow water pump. Due to the extremely low

flow necessary, this method is approximately just as expensive but is projected to be the more efficient method rather than to control the water passively through a float valve. The single drawback of this active pump is the need for a small photovoltaic to power the 3W mechanism. However, given that in many cases, the system will be utilizing water which begins at a height below that of the input to the system, such as groundwater or seawater feeds, a water pump will be necessary to pump the water up to the top of the system regardless. Therefore, an active pump is priced in the section on material costs below.

In terms of the type of water which is input into the system, the salinity of the feed stream is irrelevant to the energy usage of the system as a whole. Seawater, which has a saline concentration of 35 parts per thousand, is generally much more energetically expensive to desalinate than brackish water feeds. The ability to desalinate any salinity is therefore a key selling point for this HDH system, and will also be highlighted in the marketing section.

(2) This is the dehumidification stage of the HDH system. The purpose of the dehumidification stage is to condense the purified water vapor while collecting the heat in the input seawater. The simplified design at this step is a plate type heat exchanger made of polyethylene or polypropylene. Plate type heat exchangers work by alternating sheets of hot and cold operating fluids in close contact. These fluids have extremely high surface area contacts, thereby maximizing heat exchange between the hot and cold fluids (fig. 13). In the case of the Lienhard system, the warmer water vapor is passed in between sheets of cooler saline water, heating up the input stream of saline water such that further thermal heating steps are reduced. The now cooled and condensed water stream is then expelled from the system (9).

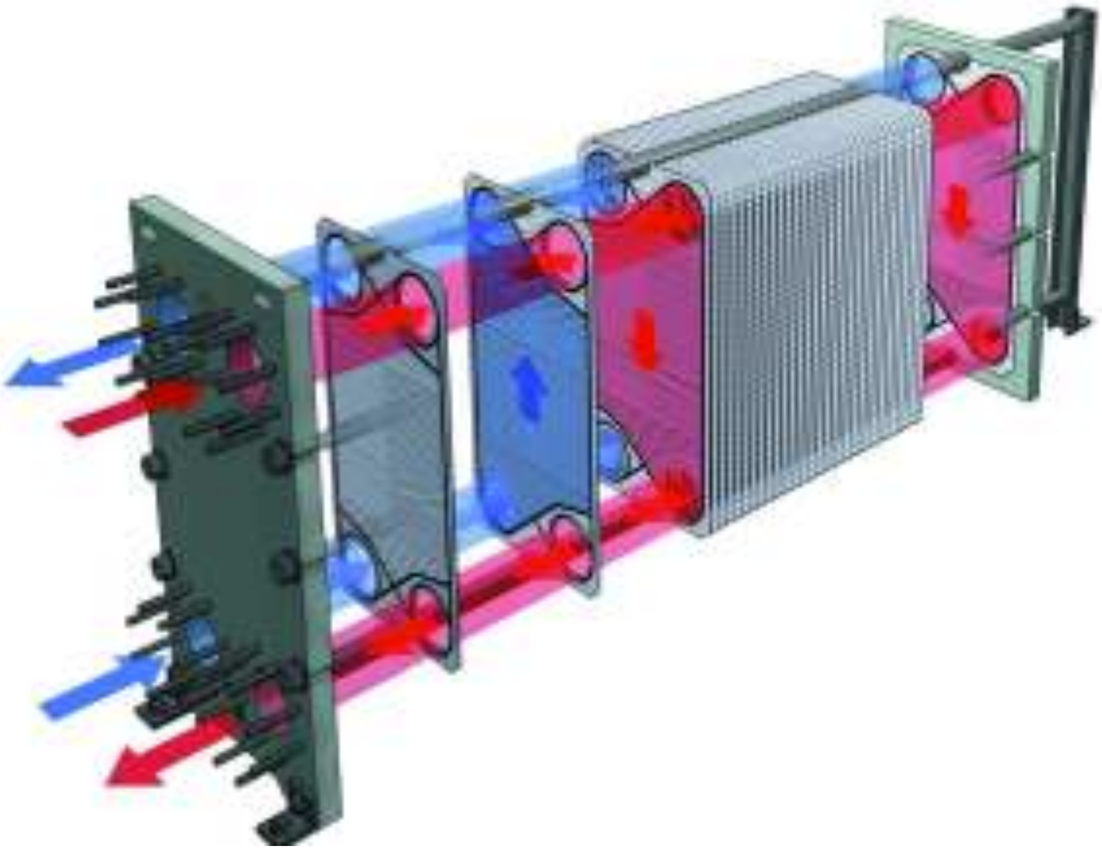

Figure 13- Common plate type heat exchangers use an alternating series of sheets, each filled with either the hot or cold working fluid. The unique efficiency of the plate type exchanger comes from the high contact area with no chance of fluid mixing. In the case of HDH technology, the hot areas are the water vapor, and the cold areas are the input saline feed [56].

Figure 14 - Prototype of solar heater. This heater is approximately 1 m^2 and can therefore process approximately $10m^3$ of purified water per day. The heater can also include a phase change material, typically a wax, underneath the surface. This material absorbs heat during the day, and releases it at night, increasing the time period operation of the heater. The tradeoff is that the heater is less efficient while the wax is being melted.

(3) Once the input feed is preheated by the condensing of the purified vapor, it is either input into the heater (fig. 14) or moves directly into the packed bed (5). As shown, the heater is made of a metal frame supporting a glass window, in which sits an absorbent black body through which the seawater or air runs. This transparent sheet allows solar radiation to enter, but does not allow thermal radiation to exit. In this way, the thermal heater can achieve the desired temperatures of 80 to 90 °C.

The heating unit can also be placed in a position where it heats the air stream instead of the water stream. If this is the case, the preheated salt water is passed directly into the packed bed, where the heated air is run through it (fig. 15). This method has several known disadvantages. First, the heated air loses some of its heat to the water in the packed bed, water which is eventually discarded and not recycled. Furthermore, the heated air is not able to obtain the same level of humidification in the packed bed as compared to originally cooler air. However, the system has not been studied in depth, and one potential trumping advantage is the increase in efficiency of the heating unit in heating a lower density air rather than water [18].

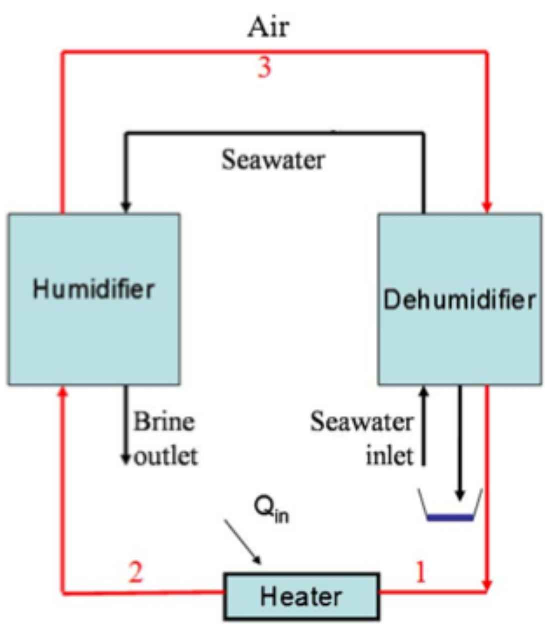

Figure 15 - CAOW air heated systems preheat the air before it enters the humidifier. While this process has not been carefully studied and is therefore not fully understood, there are several inherent disadvantages to this method which must be addressed. First, the heated air is generally not able to achieve the same level of humidification as the cooler air running through the packed bed. The heated air also gives away some of its heat to the water in the packed bed, heat which is never again recoverable [18].

The heater unit utilizes a phase change material, generally a wax, to extend the hours of performance. The heat from the solar radiation heats and melts this wax during the day. When the system begins to lose heat as night arrives or cloud cover forms, the wax begins to solidify which expels great amounts of heat to the water or air around it. This phase change material therefore allows the solar heater to operate into dark periods. The phase change material does require the redirection of some of the heat to the wax in order to melt it, and therefore slows down slightly the rate of water production during the day. Essentially, the phase change material is able to smooth out the production curve, at the cost of a reduced maximum efficiency.

Numerically, the heater is designed to absorb heat at a rate of 6 kJ/(m^2*day). The heat required to desalinate one kilogram of water is approximately 600 kJ. Therefore, in order to produce the 10 m^3/day of purified output that is projected, the system must absorb 6 kJ in that day, which sizes the heater to 1 square meter. Put in another way, 10 m^3 of purified water can be produced per 1 m^2 of heater assuming the water is slightly higher than room temperature upon entering the heating unit.

(4) This part of the system is designed to spread the saline water over the packed bed. Once again, there are several possible manifestations of this goal. Gravity driven spray nozzles can be used to disperse water over the packed bed. Alternatively, and with similar efficiency, drip irrigation lines can be run which achieve the same ends. For now, drip lines are easier to cost and more readily available in most markets, however, both spray nozzles and irrigation lines should be equal valid options.

(5) This is the humidification section of the device. Its aim is to spread the water as well as possible over corrugated metal or some other packing material, maximizing the surface area which in tern maximizes vaporization into the pure water phase. This water spreading material is known as the packed bed. The packed bed can be made of either cheaper local materials with lower efficiencies or more expensive corrugated metals which tend to provide better performance, as discussed in the optimization of humidification section above.

(6) As mentioned in the optimization of humidification section above, dry air is circulated into the packed bed either with the use of photovoltaic driven pumps or by natural convection. Natural convection is the cheaper option here. If done correctly, natural convection can be very effective, but does not have the same throughput as a air pump driven system. Therefore, the more expensive option, a photovoltaic driven air pump, will most likely provide a greater output in terms of liters per day, although the exact number is difficult to quantify theoretically. PVC pipes can be used here to carry the dry air.

(7) The humid air leaving the packed bed is then sent to the condenser unit. This can be done either through PVC pipes or simply by keeping the chambers in close quarters. All water vapor in the chamber is purified air, so anything entering the plate type heat exchanger through the air can be guaranteed to be pure.

(8) As the air stream becomes humidified and leaves the packed bed, water with a high saline content is left behind and then slowly exits the system. This water, referred to as Brine, typically has a saline concentration well above 50 parts per thousand. While dispersed brine disposal for small plants is generally not considered unsafe, there are certain environmental risks to saline water disposal repeatedly in the same area.

There are several options for completely safe brine disposal, but these are generally only necessary for large throughput desalination plants. First, the brine can be placed in evaporation pools to allow the pure water to evaporate off, leaving behind pure salt. The salt can then be sold to offset the cost of the evaporation pools. Another option is to reintroduce the brine into the feed stream. As HDH systems do not alter their energy requirements based on the saline concentration of the input stream, this option is a viable one which should not greatly degrade system performance [49].

Still, with the current knowledge, the best option for this small scale system seems to be the simple disposal of the brine is a dispersed manner. There is no comprehensive evidence that this type of low volume brine disposal is hazardous. Should new evidence crop up detailing the dangers of this method, one of the other options can be implemented, with the possible cost savings of selling the salt offsetting the construction of evaporation beds.

(9) The purified water is collected from the condensation unit. At this stage, it is almost ready for consumption. All bacteria, salts, minerals, and other contaminants have been removed from the water.

However, the water at this stage, is actually considered too pure for consumption. Water after this level of desalination is known as demineralized, as it does not contain the minerals naturally found in stream or lake water.

The regular drinking of demineralized water has been shown to have adverse affects on human patients and animals. For starters, demineralized water has been qualitatively described by subjects to be either tasteless or of poor quality. This poor taste is not trivial, in that it may push people away from the healthier water option back to the contaminated sources they are used to. Older studies have also shown demineralized water to cause alterations in the mineral concentration of the cells in the body, while others have displayed the increased chance of cardiovascular disease when calcium and magnesium are not present. Therefore, demineralized water has been declared unsafe for consumption and some minerals must actually be added added back to the water before final consumption.

There are at least two minerals which have been identified as necessary additions to pure water: Magnesium, and Calcium. Guidelines for the concentrations of these minerals in a liter of water have now been set forth. For these two minerals, concentrations should be: Magnesium-20mg/L, Calcium-50mg/L [48]. The addition of these two minerals should mineralize the water to a sufficient level to minimize most of the pure waters ill effects.

(10) Finally, in order to run the water pump and any other electrical machines used throughout the system, electrical power must be provided. The system has been designed for rural villages which are often independent of the electric grid. As such, the source of electric power must be portable and scale to small sizes easily.

Two options are currently being considered for this purpose. Photovoltaic panels, whose usage is currently spreading rapidly in rural India due to clever financing techniques, is a promising electricity source. The main problem with this source is the complex task of installation, which requires trained personal on site, often with higher than desired costs. However, photovoltaics have the benefit of being easily maintained and consistent.

A more recent development in rural electrification is the use of local waste materials, such as plant husks, to create electricity. One such company, Husk Power Systems, estimates that the cost of such a unit could be brought to $1/Watt due to the use of essentially free local materials for fuel and low installation and maintenance costs. If this technology pans out, the Lienhard group might look to install the HDH system in areas which have also installed the Husk Power Generators [81].

3.3 Considerations for Product Realization

The Lienhard group's technology, and most other HDH technology for that matter, is still in a developmental stage. Therefore, the materials, costs, patents, and technology comparisons that follow are all meant to be viewed as starting points for a deeper future analysis.

3.3.1 Considerations for Pricing the System

For the purposes of bounding the material cost of the product, two different products can be priced: a model containing the cheapest parts available (Table 1), and a model containing the most expensive parts available (Table 2).

It is important to price several different versions of the same product because different materials in the product will alter the efficiency, yet achieve the same goal. For example, in the packed bed, local loofa fills can be used, or the corrugated metal sheets can be used. Both of these materials, the loofa and corrugated metal, will achieve the purpose of spreading the water out in the humidification chamber, but each also has an associated efficiency. The corrugated metal is more expensive to install, but it is projected to increase the HDH boxes efficiency by 50% when compared to a box which uses the local fill [44].

In this way, a system can be priced which contains all of the cheapest, least efficient parts, and another can be priced which contains all of the most expensive, most efficient parts. Here, material cost refers to the cost required to purchase the parts for a system with a certain generating capacity, not the cost associated with maintaining the plant or producing the water.

In the analysis which follows, the more expensive box features four major changes which should improve the efficiency of the device: The air pump, the corrugated steel in the pack bed, the wax in the heating unit, and the photovoltaic panels. While these items are projected to improve the efficiency, they also come at a price. Therefore, it is important to determine the point at which the more expensive system becomes economically viable as compared to the cheaper system.

3.3.2 Model to Choose Between Systems of Varying Price and Efficiency

Efficiency is generally defined as:

Efficiency = e = Output / Input

For the HDH system in question, the 'Output' is the pure water production capacity of the system, and the 'Input' is the thermal energy incident on the system.

e = (Water Generating Capacity) / (kW-h Thermal Energy Input)

The thermal energy input to the system is directly related to the surface area of the greenhouse glass because it is this area which determines how much sunlight is captured by the system. The size of the greenhouse glass is what determines the total size of the heater unit which captures the sunlight. So once again:

e = (Water Generating Capacity) / (Surface Area of Heater)

Furthermore, it has been assumed in the analysis which follows that the rest of the HDH system components must be sized corresponding to the surface area of the heater. For example, if the heater size goes from $1m^2$ to $2m^2$, the amount of water which is heated per unit time will increase, so all the other features of the HDH system must double in size so that they can handle the increase in water flow. Therefore, as the heater surface area scales, so does every other component in the HDH box.

This implies a direct relationship between the sunlight input on the system and box size as a whole, where the term box size here is being used as a general reference to the size of all parts of an HDH desalination unit. If there is indeed a more nuanced relationship between each of the systems components and the heater surface area, this can be taken into account when relating the price of each component to the box size. This will be explained when each box is priced below. However, assuming that the box size does scale with heater surface area:

$$e = (\text{Generating Capacity}) / (\text{Surface Area of Heater}) = (\text{Generating Capacity}) / (\text{Box Size System})$$

Now, one can define this relationship for both a system which uses more expensive, more efficient parts, and a system which uses cheaper, less efficient parts. The efficiencies can be written as:

$$e_{expensive} = (\text{Generating Capacity Expensive}) / (\text{Box Size Expensive})$$

$$e_{cheap} = (\text{Generating Capacity Cheap}) / (\text{Box Size Cheap})$$

It is now possible to introduce a variable, ø, which relates these two efficiencies:

$$e_{expensive} = \phi * e_{cheap} \Rightarrow \phi = e_{expensive} / e_{cheap}$$

ø is the ratio of the expensive system's efficiency to the cheaper system's efficiency. This equation can be replaced with the original equations for the efficiencies to get:

ϕ = *(Ratio of Expensive Gen. Cap. to Cheap) / (Ratio of Expensive Box Size to Cheap)*

It is possible to determine the ratio ϕ experimentally. By building each of the boxes, the expensive and the cheap, with the same box size, one can then compare their generating capacities. The ratio of the generating capacity of the expensive box to that of the cheap box for two boxes built to receive the same input sunlight should produce the factor of ϕ. As noted above, the expensive system should have a higher efficiency than the cheaper system, or it would never be used as it would then always be costlier for the system with expensive parts to produce the same amount of water. This higher efficiency should manifest itself as a greater generating capacity of the expensive system for the same box size, yielding a ϕ value greater than 1.

In the process of system deployment, often the generating capacity, not the box size, for the system will be fixed. For example, a job in a village in Ghana may require a generating capacity of 50 L/day. Given this real world constraint, the generating capacities for the two systems should be set equal so the ratio of generating capacities is 1. Now, the equation relates the box size of the expensive unit to that of the cheaper unit for a given generating capacity:

Box Size Cheap = ϕ * *Box Size Expensive*

In order to make this abstract mathematical analysis slightly more real world, two boxes, the units with cheap and expensive parts, have been priced. Empirical data for the cheaper HDH system has shown that in order to produce 20 L/day, the heater glass must be $1m^2$. This production, of 20 L/day, is from here referred to as the 'Standard Generating Capacity (SGC).' It will be used to normalize the generating capacity of the boxes to that of the $1m^2$ glass size cheaper system. All other parts in the system have been sized relative to this glass sizing. The expensive system has also been sized with a heater glass of $1m^2$ and therefore the parts correspond to this heater size as well. In other words, both boxes have been equally sized (again, the system with the expensive parts should generate more water given the same box size because it is more efficient).

Not every part in the box will increase in size if the size of the heater glass is increased. For example, a water pump generally has a pumping rate which is fixed. If the generating capacity of the box is below this rate, only one pump is needed regardless of the size of the heater glass. Therefore, the number of water pumps does not scale with heater size, and is treated here as a 'fixed cost.' In the table, fixed costs are written as costs per 'Any Box Size (ABS),' indicating that these costs are fixed for a box of any size.

Other costs are variable with the size of the heating glass. As indicated earlier, the packed bed is one of these variable costs. If the heater glass size is increased by a factor of three, the size of the packed bed will also increase by a factor of three (this assumption will be discussed shortly). Therefore, the variable costs are written as costs per 'Standard Box Size (SBS),' indicating that these costs increases linearly as the box size increases relative to a set standard glass surface area of $1m^2$. These units are summarized below:

SBS = Standard Box Size = Box Sized with heater of area 1m²

ABS = Any Box Size = Used for prices not related to the size of the box

Other Terminology: Standard Generating Capacity = SGC = 20 L/day

Note that if the components in the system do not scale exactly with the greenhouse glass size, this can be taken into account through the use of pre factors in the variable costs. For example, if for every doubling of greenhouse glass size, the packed bed only increases in volume by a factor of 1.5, the cost of the packed bed can be written as ($/SBS) * (.75). If every component cost is written in this way, and then summed, the true cost equation will be obtained. However, this detailed analysis is not carried forth here due to a lack of information on how each component scales with greenhouse glass area. Therefore, the scaling has been assumed to be one-to-one.

Cheapest Model	Amount	Cost/Amount	Total	Assumptions
Water Pump	1 pump/ABS	$3/Pump [73]	$3/ABS	Each pump can move 3,500 L/day which is well above necessary

Cheapest Model	Amount	Cost/Amount	Total	Assumptions
Polyethylene	$10m^2$/SBS	\$.02/m^2 [67]	\$.20/SBS	The sheet price is close to the price for the heat exchanger
Glass	$1m^2$/SBS	\$5/m^2 [68]	\$5/SBS	$1m^2$ is necessary for 10,000 liters a day
Drip Lines	10m/SBS	\$.03/m [70]	\$.30/SBS	A snakelike configuration on roof of packed bed
Local Fills (Such as Loofah)	$2m^3$/SBS	\$.05/m^3 [44]	\$.10/SBS	Local materials, like charcoal and loofah, are cheap
A36 Steel Plates	$5m^2$/SBS	\$43.68/m^2 [71]	\$215.34/SBS	A density of 7.8g/cm3 and a thickness of .01m
PVC Piping	10m/ABS	\$.42/m [72]	\$4.2/ABS	The cheapest pipe is used, and no connections are necessary
Calcium and Magnesium	.040g/L Ca and .020g/L Mg = .06g/L = 600g/SBS	\$0.02/g [66]	\$12/SBS	Calcium and Magnesium vitamin supplements are comparable
Husk Power Decentralized Power System	3Watt/ABS	\$1/Watt [74]	\$3/ABS	This type of power system is available in the village

Table 1 - The model using the cheapest possible parts is shown above. Every feature has been chosen to reduce the price, regardless of the effect on efficiency. Where possible, passive processes, such as natural circulation have been chosen over electrically active processes. For the local fills, a price of five cents has been set arbitrarily for safety, as the Shannon Liburd analysis suggests that the price of local material is cost-free [44].

Costliest Model	Amount	Cost/Amount	Total	Assumptions
Water Pump	1 pump/ABS	\$3/Pump [73]	\$3/ABS	Each pump can move 3,500 L/day which is well above necessary

Costliest Model	Amount	Cost/Amount	Total	Assumptions
Polyethylene	$10m^2$/SBS	\$.02/m^2 [67]	\$.20/SBS	The sheet price is close to the price for the heat exchanger
Glass	$1m^2$/SBS	\$5/m^2 [68]	\$5/SBS	$1m^2$ is necessary for 10,000 liters a day
Wax	$.1m^3$/SBS	\$1080/m^3 [69]	\$108/SBS	A .01m thick layer of wax sits on the base of the heater
Drip Lines	10m/SBS	\$.03/m [70]	\$.30/SBS	A snakelike configuration on roof of packed bed
Corrugated Metal For Packed Bed	$10m^2$/SBS	\$4/m^2 [76]	\$40/SBS	Local materials, like charcoal and loofah, are cheap
A36 Steel Plates	$5m^2$/SBS	\$43.68/m^2 [71]	\$215.34/SBS	A density of 7.8g/cm3 and a thickness of .01m
PVC Piping	10m/ABS	\$.42/m [72]	\$4.20/ABS	The cheapest pipe is used, and no connections are necessary
Calcium and Magnesium	.040g/L Ca and .020g/L Mg = .06g/L = 600g/SBS	\$0.02/g [66]	\$12/SBS	Calcium and Magnesium vitamin supplements are comparable
Air Pump	1 Pump/ABS	\$3/Pump[75]	\$3/ABS	The pump can move >3000 L air/day
Photovoltaic Panels Installation	1 Single Time Installation Cost	\$200/Installation	\$200/ABS	Requires Specialized Labor
Photovoltaic Panels	3Watt/Water Pump + 2.5 Watt/Air Pump = 5.5Watts	\$1.68/Watt [74]	\$9.24/ABS	Photovoltaics costs scale linearly with wattage required

Table 2 - The unit, containing the most expensive parts, is detailed above. Every feature has been chosen to increase the price in order to maximize the efficiency. Where possible, active processes, such as forced circulation and water pump control of pressure, have been chosen over passive processes. Note that many of the materials have stayed the same as they are necessary in every manifestation of the product.

The generating capacity required for a job is generally set by the conditions of the market. It is therefore valuable to determine which system should be used for a given size of job. For example, which system, the cheaper or the more expensive manifestation, should be used for a job which requires a box with a generating capacity of 100 L/day?

One can assume without losing generality that the relative box size is some function of the relative generating capacity:

Box Size/SBS = function(Generating Capacity/SGC)

For a simplistic model, this functional dependence can be assumed to be linear (if the dependence is shown to be nonlinear, the following mathematically formulae must be amended). A linear relationship between these two variables denotes that in the real world, as desired normalized generating capacity is increased, box size increases by some linear factor:

*Box Size/SBS = æ * Generating Capacity/SGC = æ*x'*

Where x' has been used here as the normalized generating capacity. The material cost of each system takes the form of a line which is dependent on box size. The standard formula for a line is:

$$y = mx + b$$

Where:

y = Total Materials Cost

m = Sum of the Costs which Scale with Normalized Box Size

x = Normalized Box Size

b = Fixed Cost Per Box

It is clear from the tables above that the slope, m, is dependent on normalized box size. However, the variable of interest is the generating capacity. Therefore, this line equation should be rewritten in terms of the normalized generating capacity as:

*Total Materials Cost = (Sum of Costs which Scale with Normalized Box Size) * (æ * x') + (Fixed Costs)*

This is the general equation for finding the total installed price of a system given a certain desired normalized generating capacity. To generalize, ø is left as a variable in the analysis. In order to find the point at which the total materials costs for the two systems are equal for equal generating capacities, one need only set the total materials cost equations equal and solve:

$$y = y_{expensive} = y_{cheap}$$

$$m_{cheap} * x_{cheap} + b_{cheap} = m_{expensive} * x_{expensive} + b_{expensive}$$

Assuming the generating capacities are equal one can relate the box sizes through ø:

*Box Size Cheap = ø * Box Size Expensive*

$$m_{cheap} * x_{cheap} + b_{cheap} = m_{expensive} * (1/\phi) * x_{cheap} + b_{expensive}$$

$$x_{cheap} = \phi\ (b_{cheap} - b_{exp}) / (m_{exp} - \phi * m_{cheap})$$

$$x_{cheap} = œ_{cheap} * x'$$

$$\boldsymbol{x' = \text{Normalized Generating Capacity} = \phi\ (b_{cheap} - b_{exp}) / (œ_{cheap} * (m_{exp} - \phi * m_{cheap})}$$

Now, plugging back in to solve for the total cost y:

$$\boldsymbol{y = \text{Total Material Cost at Crossover} = m_{cheap} * (\phi * (b_{cheap} - b_{exp}) / (m_{exp} - \phi * m_{cheap})) + b_{cheap}}$$

Therefore, these equations, which relate ø to the generating capacity crossover point and the total materials cost at which this crossover point occurs, can now be used for any two differently priced systems. For the two systems priced with a heater glass size of $1m^2$:

Cheap Unit Material Cost = 10.20 + 232.94 * (Capacity/SGC)

Expensive Unit Material Cost = 219.44 + 380.84 * ((1/ø)*Capacity/SGC)

To produce X liters of water for a value of ø = 2 and œ = 1:

Generating Capacity (Liters)	Box with Cheaper Parts: Total Material Cost ($)	Box with Expensive Parts: Total Material Cost ($)	Box with Cheaper Parts: Cost per Liter Generating Capacity ($/L)	Box with Expensive Parts: Cost per Liter Generating Capacity ($/L)
20	243.14	409.86	12.16	20.49
60	709.02	790.70	11.82	13.18
100	1174.90	1171.54	11.75	11.72
140	1640.78	1552.38	11.72	11.09
180	2106.66	1933.22	11.70	10.74

Table 3 - For an expensive system which is twice as efficient as the cheaper system (ø=2), each system has been priced. The per liter cost is also given. Note that the per liter generating capacity cost is about $12. This is about 10x greater than the material cost of RO systems. This cost should be mitigated by ease of use, cost of maintenance, and marginal cost of water.

The $/(L generating capacity) material cost are about $12/(L generating capacity). The material cost of $12/L is about 10x higher than the material cost of traditional large scale reverse osmosis costs per liter generating capacity. However, the price and ease of maintenance and the use of free solar energy, which has not been shown here, should bring these costs closer together as the water from the HDH system is actually produced and sold.

For these two cost equations, for different values of ø but again with œ assumed to be 1, the crossover capacities (the normalized generating capacities at which the prices are the same), and the corresponding unit prices, are given in the table below:

Phi (Efficiency Expensive/ Efficiency Cheap)	Crossover Capacity ((Generating Capacity) / (20L/day))	Cost At Crossover Point ($ installed cost)
1	Always Use Cheaper System	Crossover Point Negative
1.25	Always Use Cheaper System	Crossover Point Negative
1.5	Always Use Cheaper System	Crossover Point Negative
1.75	13.66	3192.28
2	4.92	1156.49
2.5	2.60	614.89
3	1.97	470.04

Table 4 - If the efficiency ratio is <1.5x the cheaper system is always the better choice regardless of the generating capacity desired. If the expensive system is >1.75x more efficient than the cheaper system, than the normalized generating capacities at which the more expensive system should be used are shown above. Finally, the price at which the crossover from the cheaper to more expensive system is shown in the final column on the right.

Note that this table is very dependent on the actual fixed and variable costs of the two systems. If the items in each system and the costs of those items are better determined, this crossover capacity and cost per liter will become far more accurate.

The main purpose of the above analysis was to derive equations for deciding between systems of different efficiencies, and the table above is only meant to illustrate how this set of equations might be used. To reiterate, if a choice is to be made between multiple systems with different material cost equations and different efficiencies, the above analysis should aid in making a concrete choice of system for a given generating capacity.

3.3.3 Patent Portfolio

The field of humidification dehumidification is relatively new and does not have a robust set of IP standing in the way of new innovation. However, it is still important to understand the nature of the current legal field, and note the potential for a technology roadmap which does not violate any of the patents currently operating in the United States or the International arena. A summary of the patents relevant to the deployment of HDH technology is presented (Table 5). As U.S. patent law dictates that any patent filed before June 8, 1995 will last 17 years from the filing date, whereas patents filed after this date have a 20 year lifetime, only patents listed after 1994 are listed below. There is also a distinction between US and international patents. For those patents which have a “US” before their filing number, they are only valid in the United States. An international patent would have to be in place if operations in other countries, such as India and Ghana, were to be filed in violation of the IP.

Name-Number-Date	Description	Claims
Hybrid Solar, Desalination System - US20100314238 - 04/30/2010	• Hydro-Thermal Exchange Unit (HTEU) to convert seawater to vapor and then condense it on the input seawater stream • Loose description of a packed bed and solar heater which induces evaporation of the seawater • Describes a system for multiple vapor tubes to extract air at multiple humidity levels • System uses at least 1 solar panel to drive a pump which moves vapor	• A HTEU which includes paths for feed water, vapor and fresh water. It also includes a solar collector, an evaporator, and a condensation unit where heat is put back into the input stream. • Photovoltaic module with at least one pump powered by the energy • A solar collector leading to some feed stream evaporation
Desalination Method and Apparatus - WO2007128062A1 - 05/04/2007	• Humidification dehumidification technology which uses a carrier gas instead of air to transport the water vapor. Preferred carrier gasses are Hydrogen, Helium, and Ammonia • The maximization of three key ratios of the carrier gas to water vapor properties compared to air to water vapor properties are preferable. These property ratios are: Gas constant, specific heat, and thermal conductivity	• Carrier gas is used as a substitute for air in an otherwise conventional HDH system • Carrier gas is in a closed loop system • Carrier gas has properties consistent with those described previously, or consists of any of the three gasses: H_2, He, or NH_3 • A prescribed method for carrier gas selection
Diffusion driven water purification apparatus and process - US20050230238 - 06/16/2005	• Low pressure waste steam is drawn from power plant, combustion engine, or solar heating • This heated air stream is moved by diffusion through a packed bed with seawater or brackish water feed in high surface area environment • Humidified air is then condensed in spray of pure water already desalinated • Dry air stream reheated and circulated back into packed bed	• The use of low pressure waste heat from a power plant • The use of spray nozzles to cover the packed bed, as well as the use of at least one impurity in the pack bed to create higher surface area • The use of liquid to humidify the air stream in the condensation stage

Name-Number-Date	Description	Claims
Process for Desalinization Utilizing Humidification/ Dehumidification - US6607639 - 08/17/2001	• Seawater is heated using solar collectors and passed into an evaporative unit. • Heated seawater is then put into a chamber with cooler fresh water such that evaporation of the seawater is encouraged by the cooler waters circulation. • Fresh water is collected, and new seawater is brought into the system	• A method of introducing salt water into thermally favorable environment for evaporation to occur • A process of maintaining a temperature difference of between 50 and 75 degrees Fahrenheit
Method and apparatus for simultaneous heat and mass transfer utilizing a carrier-gas at various absolute pressures - US20050121304 - 12/03/2004	• The patent details a broad method for separating out a liquid from interstitials while operating below the boiling point of the liquid. • The pressure of the chambers is varied in order to maximize the evaporation of the liquid. • This method is specifically discussed in relation to the desalination of water, however the carrier gas is not specified.	• A method for separating a liquid component from its mixture by varying the pressure and allowing thermal contact • Essentially, a traditional HDH system with compressor and air release valves
Solar Desalination System - US20100275599 - 05/01/2009	• A classic humidification dehumidification process is described with the caveat of creating electrical energy using a steam turbine and water turbine when condensing the water. • Essentially, instead of water being used heat the incoming seawater, all heat is converted to energy, and more heat is collected from the sun to heat the water initially.	• The addition of the electrical generators to regain energy from condensing water vapor • A sun tracking solar energy collector with one of three parabolic shapes • Auxiliary heating source which kicks in when solar heating is insufficient

Table 5 - The landscape of relevant patents filed in the field of HDH by other companies and universities is listed. Some of these patents are broad and describe HDH systems in general, but the claims are also broad and more difficult to enforce. Others, such as the patent on carrier gas variation or energy generation system are much more specific and any technology overlap with these patents should likely be avoided. Overall, the HDH field is open to innovation as the number of patents is relatively small, while the state of the technology is at a nascent development stage.

The Lienhard group has also begun to file patents to protect its technology. The first of its five filed patents, filed September 9th, 2009, attempts to improve the HDH system by reducing the pressure of the carrier gas within the humidification and dehumidification chambers in order to improve the efficiency of the system. This patent should allow for product maneuverability should the efficiencies of the current thermal system need improving. More patents are in the pipeline, and should create a solid platform on which to legally expand the HDH technology into diverse markets.

3.4 Technology Comparison

Each of the technologies detailed in the previous two sections has certain pros and cons. Each technology has constraints under which it preforms best, and certain resources which it requires to preform at all. Therefore, in order to understand where the Lienhard group's HDH system has an advantage over the competitors, a thorough comparison follows.

Note: As Electrodialysis Reversal is not able to desalinate seawater but only brackish water, and has extremely high electrical energy usage, its data is not relevant here as it is not a direct competitor to the HDH system in the market being considered.

Energy Used	**Thermal**			**Membrane**
Process	MSF	MED	HDH	RO
State of the Art	Commercial	Commercial	**Development**	Commercial
World Wide Capacity 2004 (Mm^3/d)	13	2	0	6
Heat Usage (kJ/kg)	250-330	145-390	30-300 [18]	--
Electricity Consumption (kWh/m^3)	3-5	1.5-2.5	1.20 [18]	2.5-7
Plant Cost ($\$/m^3/d$)	1500-2000	900-1700	12,000 [Sec. 3.3.1]	900-1500
Average Production Capacity (m^3/day)	100,000 [8]	50,000 [8]	<10	100,000 [8]
Plant Cost for Average Production Capacity (Million $)	175	67.5	**0.12**	120
Operating Cost ($\$/m^3$)	4.30 [59]	4.30 [59]	3-7 [18]	2.57 [59]
Conversion Freshwater/ Seawater	10-25%	23-33%	25%	20-50%
Max Top Brine Temperature (^oC)	90-120	55-70	80-90	45(max)

Energy Used	Thermal			Membrane
Reliability	very high	very high	**very high**	moderate
Maintenance (cleaning/ year)	0.5-1	1-2	**1**	several times
Pre-treatment of Water	simple	simple	**very simple**	demanding
Operation Requirements	simple	simple	**very simple**	demanding
Water Quality (ppm)	<10	<10	<10	200-500
Energy Usage Per Increase Feed Salinity	low	low	**none**	high
Time to Commissioning (Months)	24	18-24	**1-2**	18

Table 6 - The HDH system is not a clear winner in every important category of comparison. However, many of its shortcomings are also its strengths. Its low production capacity makes it ideal for smaller markets. Its lack of commercial capacity means the market is open to alternatives. Finally, slightly higher energy use is mitigated by the use of sunlight as energy rather than electrical or mechanical energy from power plants [57].

The most important points of comparison have been bolded in the table above. To reiterate, there are a few major advantages that the HDH process has:

The HDH system can scale to small generating capacities with no sizable reduction in system efficiency. The system is extremely easy to repair which can be done by uneducated villagers. This is in stark contrast to most of the other systems which require trained personal to attend to the system. Finally, the use of solar energy, which is abundant and free in many parts of the rural world, makes the operating cost of HDH lower and the system much more reliable.

These comparisons, among others, are summarized in the following table, taken from “An Integrated Assessment of the Suitability of Domestic Solar Still as a Viable Safe Water Technology for India” by Santosh Avvannavar [80].

Technologies	Pros	Cons
Membrane Technologies	• Can remove dissolved constituents • Can disinfect treated water • Can remove organic compounds • Can remove natural organic matter and inorganic matter • Reduces labor requirements; can be automated easily • Smaller space requirements; membrane equipment requires 50 to 80 percent less space than conventional plants	• Works best on ground water or low solids surface water or pretreated wastewater effluent • Lack of reliable low-cost method of monitoring performance • May require residuals handling and disposal of concentrate • Expensive compared to conventional treatment • Require replacement of membranes about every 3 to 5 years 6. • Scale formation can be a serious problem. Scale-forming potential difficult to predict without field testing • Flux rate gradually declines over time. Recovery rate may be considerably less than 100 percent 8. • Lack of a reliable low cost-method of monitoring performances • Rejects particles as small as 0.0001µm.
Electrodialysis	• Adaptable to various operation parameters • Require little labor and the maintenance cost is low	• Treatment cost is directly related to TDS concentration in feed water • Best suited up to 4000mg/L TDS • Short Design Life • Membrane cleaning (backwashing or chemical treatment), high membrane replacement cost, low resistance to chlorine, and lack of resistance to fouling.
Chemical Methods	• Feasible for removal and recovery of metals	• Extensive pre-treatment is required • Concerns about life of ion-exchange resins • Complex regeneration system required

Technologies	Pros	Cons
Solar Distillation Methods	• Low energy cost • Low material, maintenance and equipment cost • Ultra-pure water	• Requires large amount of land and direct sunlight • Low productivities • Scaling and corrosion (medium and large scale and material used) • Disposal of concentrated waste

Table 7 - A more qualitative comparison highlights the low operational necessity of solar distillation methods, while displaying the barrier to entry of more complex, more repair heavy systems. While there are certainly pros and cons to every system, rural markets, as will be seen shortly, are best served by solar distillation methods [80].

4. Markets

Target markets have been identified by focusing first on areas where there is a desperate need for desalination. This list has been further pared down by keeping only areas where the available and necessary resources for HDH implementation are present, namely: abundant sunlight and local salt water. Regions with too much money and too much energy are struck from the list for HDH adoption. Excess money and electricity play to the strengths of higher cost, higher efficiency competitor technologies, such as reverse osmosis, allowing them to gain a competitive advantage. Finally, education level is used as a discriminating factor as one of HDH's main strengths is that it does not require educated people to maintain, areas which are very well educated can implement small scale RO systems more easily. Finally, certain regions in Africa are currently extremely unstable politically, and are no longer viable for execution of a stable market strategy at the time of this paper's writing.

To reiterate, the following criteria are characteristics a target market must have:

1) Water scarcity in order to ensure demand for desalination
2) High availability of thermal energy in order to drive the solar thermal driven heater
3) High village density near coastlines to decrease distribution costs and maximize impact
4) Restricted buying power to prevent competitors from entering the market
5) Restricted energy availability to prevent more efficient competitor technologies such as reverse osmosis from being viable

6) Reduced educational proficiency so that easy maintenance is a must
7) Other discriminating factors such as political stability are used to minimize unforeseen regulation, market, and safety changes for implementation

Finally, the narrowed list of potential markets is compared and contrasted so as to suggest a plan for market penetration.

4.1 Narrowing the Global Market

Prior to analysis, the entire world must be considered a potential market. In the this era of globalization and the "flat" planet, there are virtually no areas on earth that are unreachable. Therefore, it is prudent to start the search for potential markets by considering the world as a whole, then eliminating markets in the order of the criteria set forth in the introduction to this section.

Through this analysis, India, Ghana, and Eastern Africa have been selected for further analysis. Of these, this paper has specifically looked further into India. This does not mean Ghana or Eastern Africa are any worse off as markets, simply that material on their water situations is a bit more nascent and should be the subject of future work. Finally, inside India, the district of South 24 Parganas has been chosen as the target district for initial deployment.

While the market analysis concludes by citing this district as the target, this does not mean that HDH technology is only viable in this district. Rather, it implies that this district is a good starting point, from which HDH can branch out.

4.1.1 Scarcity of Clean Water

If enough clean water is available, it is generally not necessary or cost effective to desalinate more water simply to increase supply. Therefore, every region which is not currently suffering from some form of clean water scarcity should be avoided when targeting the market due to insufficient demand. The map of regions with water shortages is split into red regions, which represent areas currently suffering from physical water shortages, and orange regions, which represent economic scarcity, denoting the inability of people to purchase sufficient water at the rates provided. Pink regions may require water solutions soon and blue regions currently have enough water. The circles on the following maps highlight areas of interest (fig. 16).

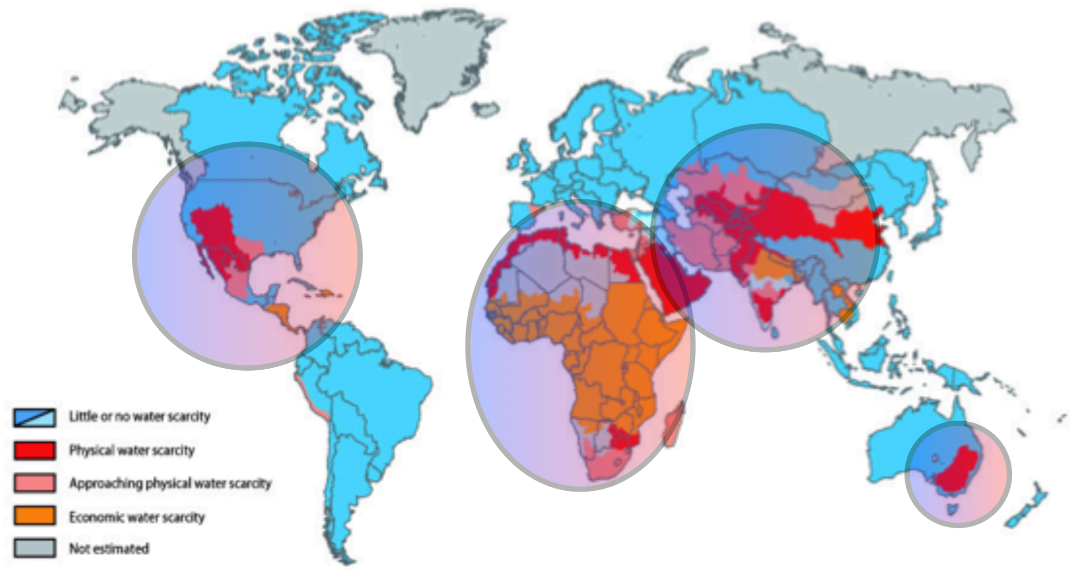

Figure 16 - The red and orange regions show severe water shortages. The water shortages in these regions imply that a demand for solutions exists [79].

4.1.2 High Availability of Thermal Energy

While water scarcity is a necessary criterion for a target market, it is not sufficient. If solar energy is not available in abundance, one of the key advantages of the HDH system is lost. Moreover, the HDH system without sufficient solar energy will not function to full capacity, and will not satisfy its projected output. Therefore, regions which do not have sufficient solar energy will not be targeted, regardless of their water scarcity situations. Interestingly enough, the regions which are short on water also tend to have abundant solar radiation. Therefore, this map, while necessary, does not eliminate from the list of potential markets any of the countries not already struck down. This is good news for HDH technology, as it is a viable option in every region which requires it (fig. 17).

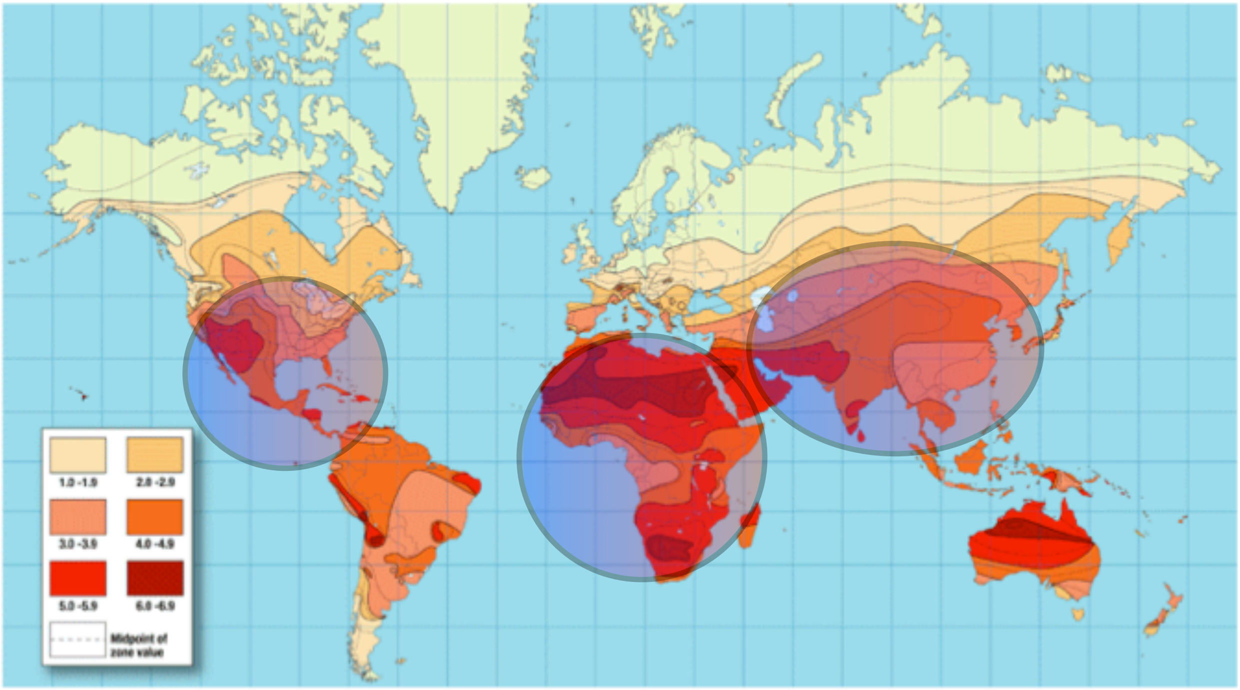

Figure 17 - The map of solar radiation across the globe does not lead to the further narrowing of the list. There is significant crossover between water starved regions and of regions with substantial solar radiation. This bodes well for HDH, as the technology is implementable in most of the regions which demand it [79].

4.1.3 High Population Density

Another key advantage of the HDH system is its price. Keeping the price low differentiates HDH technology from the other desalination technologies, but also reduces the profit margins when selling the product. Businesses can make up for low margins, but generally do this with a high volume of sales. Therefore high population density is a criterion for target markets. In the initial stages of product implementation, the greater the number of products which can be sold in a tighter geographic area, the more money which can be saved in distribution and manufacturing costs.

Furthermore, populations which are closer to the coast will have greater access to seawater. HDH desalination does not use more energy to desalinate saltier feeds, and as such, has a big advantage over RO and EDR when desalinating seawater. Moreover, communities which can readily access seawater are more likely to have a cheap supply feed for desalination. While proximity to sea water is not a deal-breaker for the HDH system as it can also desalinate brackish water, it is a good method of reducing the preliminary target markets to ensure that an essentially endless water supply exists (fig. 18).

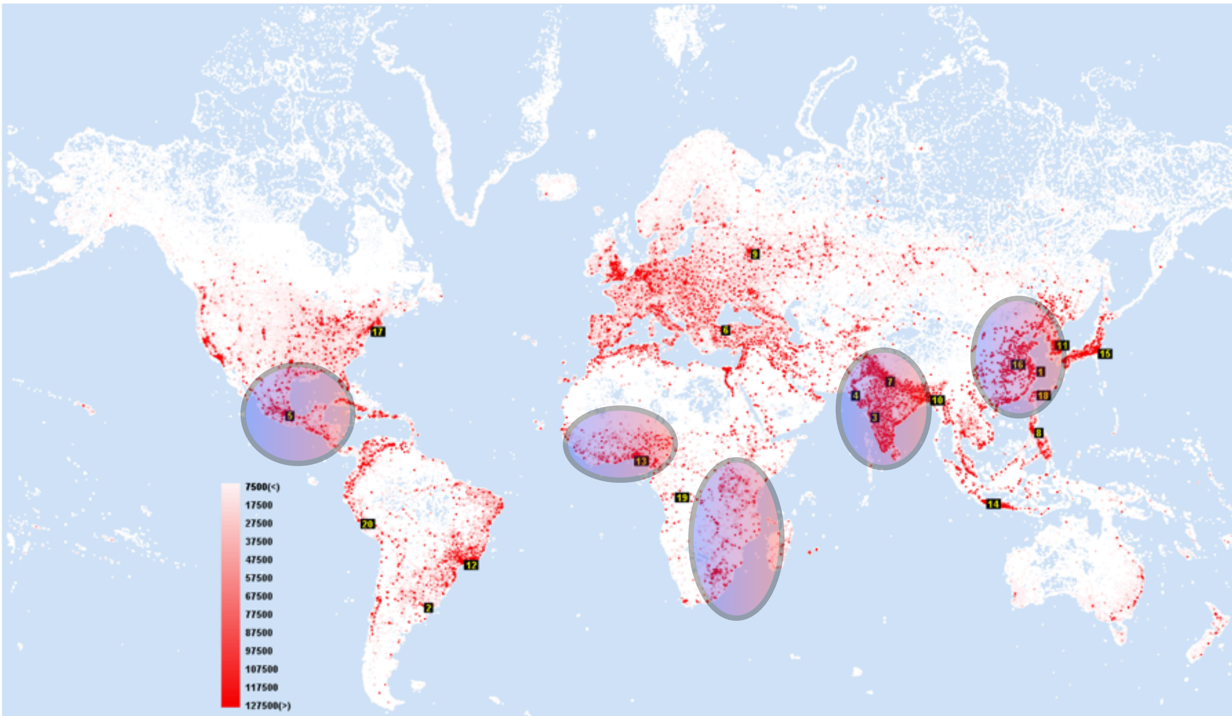

Figure 18 - Here population density is taken into account when targeting markets. Most of the regions previously circled are still present. Some regions have been eliminated because the populations are too small to justify the costs of distribution and advertising [60].

The regions which are now viable markets can be further narrowed. Note that on all maps, the target circles will only be drawn over area which have already been cited as possible targets by previous criteria. For example, Europe is clearly population dense but has not been circled above because it did not meet the previous demand criteria.

4.1.4 Restricted Buying Power

As already noted, price is a key benefit of HDH technology. Regions where economic prosperity is low are more likely to adopt low cost systems rather than high cost alternatives, even if efficiency suffers. Therefore, target markets can be further reduced by removing areas which can adopt other technologies, and focusing on those areas where market competition from higher resource technologies is not a factor (fig. 19).

Areas which cannot adopt reverse osmosis and other thermal processes help to pare down the list of target markets further. The United States and Australia can be stricken from the list immediately. India and Western and Eastern Africa should be investigated further.

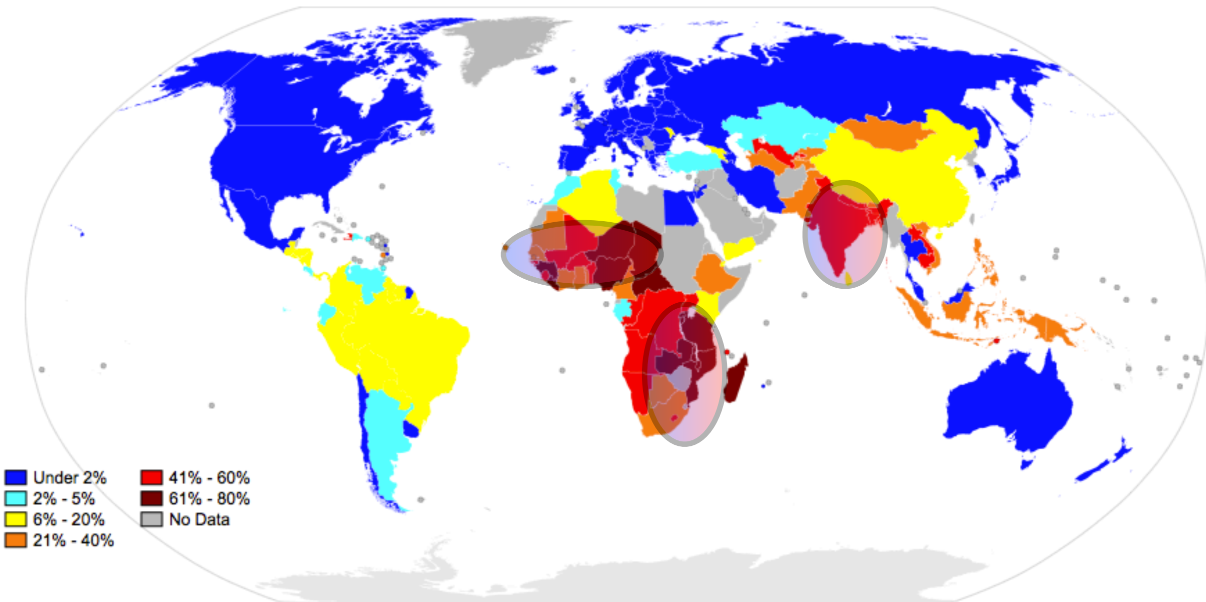

Figure 19- Country by country percentages of population living under $1.25 a day in 2009. Note that India and the Western and Southern reaches of Africa seem to be the poorest areas which also have a close proximity to seawater. This poverty level is desirable for a target market because it eliminates competition from higher-efficiency higher-cost players such as Reverse Osmosis and MSF. Statistics from UN Human Development Report, 2009 [46]. Map compiled open source on Wikipedia [47].

4.1.5 Restricted Electrical Energy Availability

The HDH system proposed does not require any *external electrical* energy to run. This is another huge advantage when compared to reverse osmosis and electrodialysis methods available on the market today. The lighter areas display regions with little electrical power usage per capita (fig. 20).

The areas with low electrical availability are prime candidates for targeting, however, just as the solar energy map did not lead to the elimination of any target areas, neither does the electrical usage map. There is a corresponding match up of monetary resources and electrical availability. Of course, this follows naturally as countries with more money per capita will build up their electrical capabilities. This match up validates further the elimination of regions due to the monetary categorization, and solidifies the list as thus far.

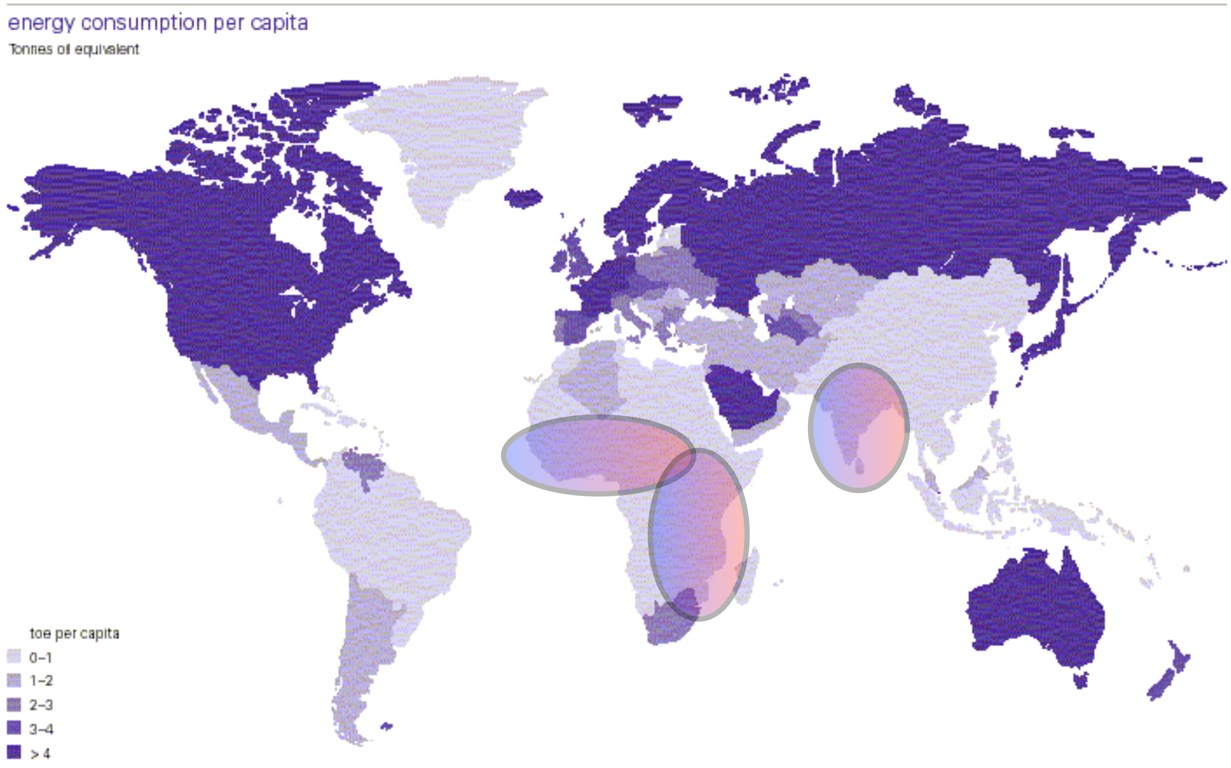

Figure 20- Per capita global electricity usage rates. The lower the availability of electrical energy, the less likely alternate energy intensive desalination methods are to be used. The electrical energy map and the income maps match up well, so no further reductions in target market can be garnered from this electrical analysis. The map does solidify those areas eliminated by the income analysis [10].

4.1.6 Education Level

The HDH system is much easier to repair than its competitors. RO and EDR both require skilled technicians to repair and replace membranes. These technicians must also be able to identify potential electrical wiring problems, as well as problems with pump pressure and pretreatment methods. The other thermal methods are no easier to maintain. MSF and MED both require skilled technicians to correct fouling problems. Moreover, the heat sources to these units are often even more complicated than the units themselves (often MSF and MED use waste heat from power plants), so MSF and MED can suffer from complex maintenance problems farther up their heating supply line (maintenance requirements in the power plant supplying their heat).

The simplicity of the HDH system makes it extremely easy to maintain. By using parts with extremely low rates of failure, and by utilizing no active heating elements aside from the sun, the HDH system requires very little knowledge of complicated systems to maintain. Therefore, to prevent market penetration by other technologies, literacy rates are used as a tool to assess general education level. Countries which are too well educated should not be targeted, because it is more likely that these areas will be able to adopt more complex technologies and have the wherewithal to repair them.

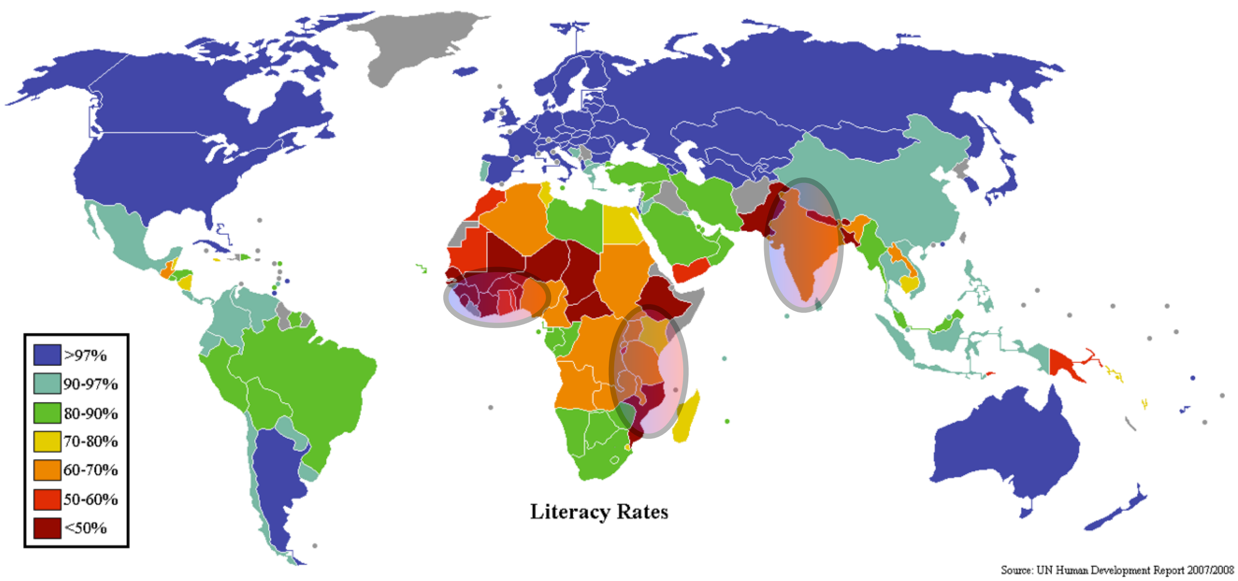

Figure 21 - Global literacy rates have been used here as a measure of the overall education level of a country. The less educated a country is, the less complicated a technology must be to be used by the uneducated in the society. This favors HDH over other methods, and has been used as a means of further market discrimination. Still, Western and Eastern Africa, and India, are left [83].

4.1.7 Further Target Market Contraction

From the market analysis and exclusion principles used above, the regions which have passed every qualification are: India and Eastern and Western Africa. This list can be further pared down.

Much of Western Africa is unstable, the Ivory Coast is currently on the brink of civil war due to a recent presidential battle. The election in the country was disputed by incumbent President Laurent Gbagbo. Gbagbo has refused to step down from power, and the opposition candidate, Alassane Ouattara, had been trying to gain control by shutting down all income streams to the government. Consequently, foreign business had been fleeing from the country rapidly [61]. Although the conflict recently came to an end, the business climate is still reeling, and should be avoided. Sierra Leone, Nigeria, and Liberia recently came out of brutal civil conflicts which left hundreds of thousands dead and have introduced new governments still struggling to find their footing. The region in general has been plagued by conflict, and does not look to be leaving this state any time soon.

There is one diamond in the West African rough, and that is *Ghana*. Ghana has been consistently praised by the international community for its open economy and stable government. Ghana was the main stop on a presidential visit to the country by Barack Obama in 2009, in which President Obama, while stating the distance the country still has to go, praised Ghana for its progress, and hailed it as a model for other nations to follow. Ghana is also home to a large number of non-governmental organizations who have been serving the rural community for decades. Economically speaking, Ghana is on a path which looks very good for entering businesses. Trading Economies, an online database of economic statistics recently wrote, "Ghana's has one of the highest GDP per capita in West Africa. The country has a diverse and rich resource base with gold, timber, cocoa, diamond, bauxite, and manganese being the most important source of foreign trade. In 2007, an oilfield which may contain up to 3 billion barrels of light oil was discovered. Yet, in spite of abundance of natural resources, a quarter of the population lives below the poverty line." [62] This makes Ghana the perfect West African nation for further study.

As India and Eastern Africa both seem conflict free at the moment and both of their projections for business are bright, they are not edited from the list. Therefore, these three areas: India, Ghana, and Eastern Africa should be investigated further.

4.1.8 Final Target Regions

By overlaying the favorable sections of all of the above maps, and by excluding those regions with other problems mentioned in section 4.1.6 above, a map composed only of those regions which meet all of the criteria set forth is produced. This map gives a global snapshot of regions which are ripe for further exploration (fig. 22). These regions are the India, Ghana, and Eastern Africa.

Of course, these are huge areas. A marketing plan that simply stated that these massive geographic regions should be targeted would really say nothing about the actual communities which are worth exploring. To this end, the Indian market is investigated further below. The two African regions have not been further explored because information on their individual districts is still very hard to come by. As these countries become more developed and their tracking data becomes better informed, Ghana and Eastern Africa should be further dissected as well.

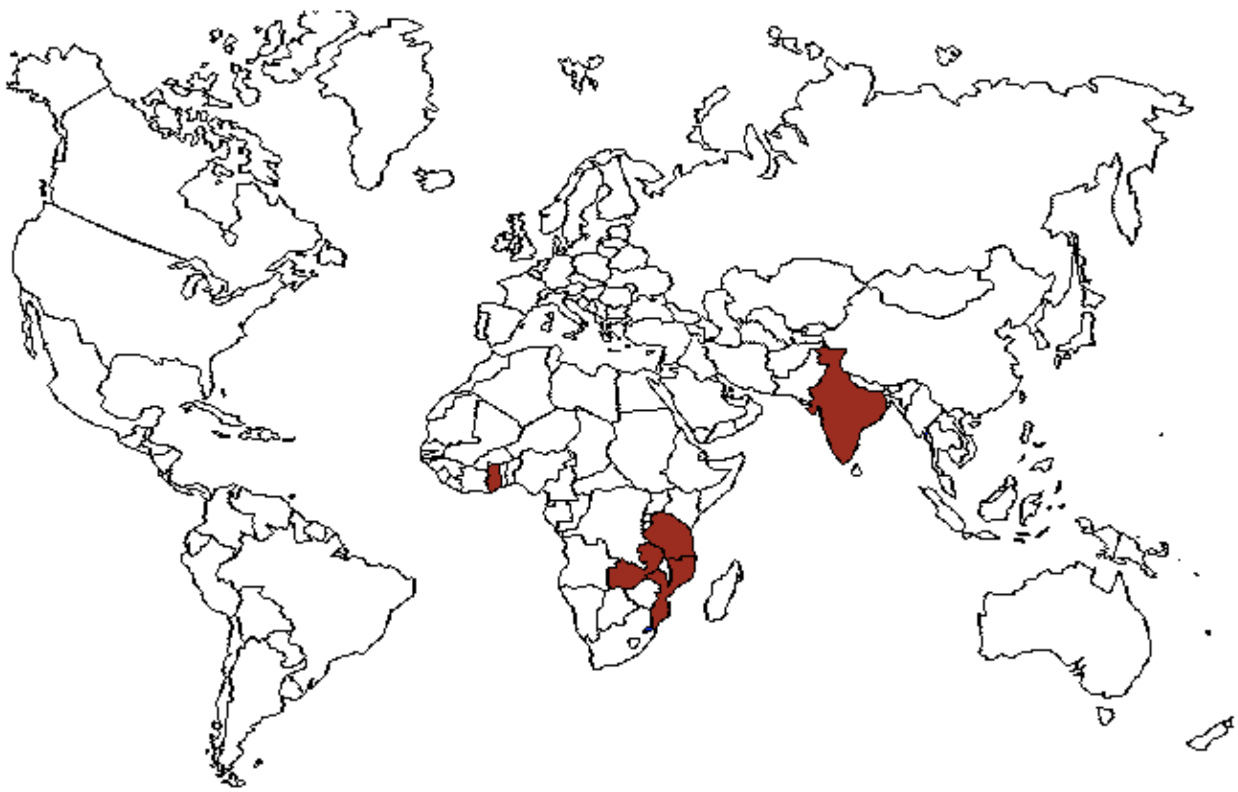

Figure 22 - After excluding every country where there was no demand, alternative supply, or other issues with the market stability, only these three regions have been left: India, Ghana, and Eastern Africa. However, due to the limited supply of information regarding Ghana and countries in Eastern Africa, only India is investigated further.

4.2 Deeper Investigation of Indian Market

The same market analysis which was used to narrow the global market to the Indian and African markets can again be applied to India itself in order to find areas within the country which are potentially interesting for initial deployment. The initial global maps used were quite broad, so a more pointed analysis should provide better targeting as to which regions of this large country are actually attractive.

Indian Clean Water Scarcity:

As previously mentioned in the paper, India is projected to see moderate to severe water scarcity almost across the entire country. Only a few select regions are projected to be spared from any sort of crisis given current levels of supply and projected levels of demand. Figure 23 displays this bleak future for the water crisis in India should supply stay constant. The regions on the map are separated into river beds, and their future supply has been approximated based on static policy and current levels of productivity and efficiency. Note that WFR indicates a western flowing coastal river basin and EFR indicates an eastern flowing coastal river basin.

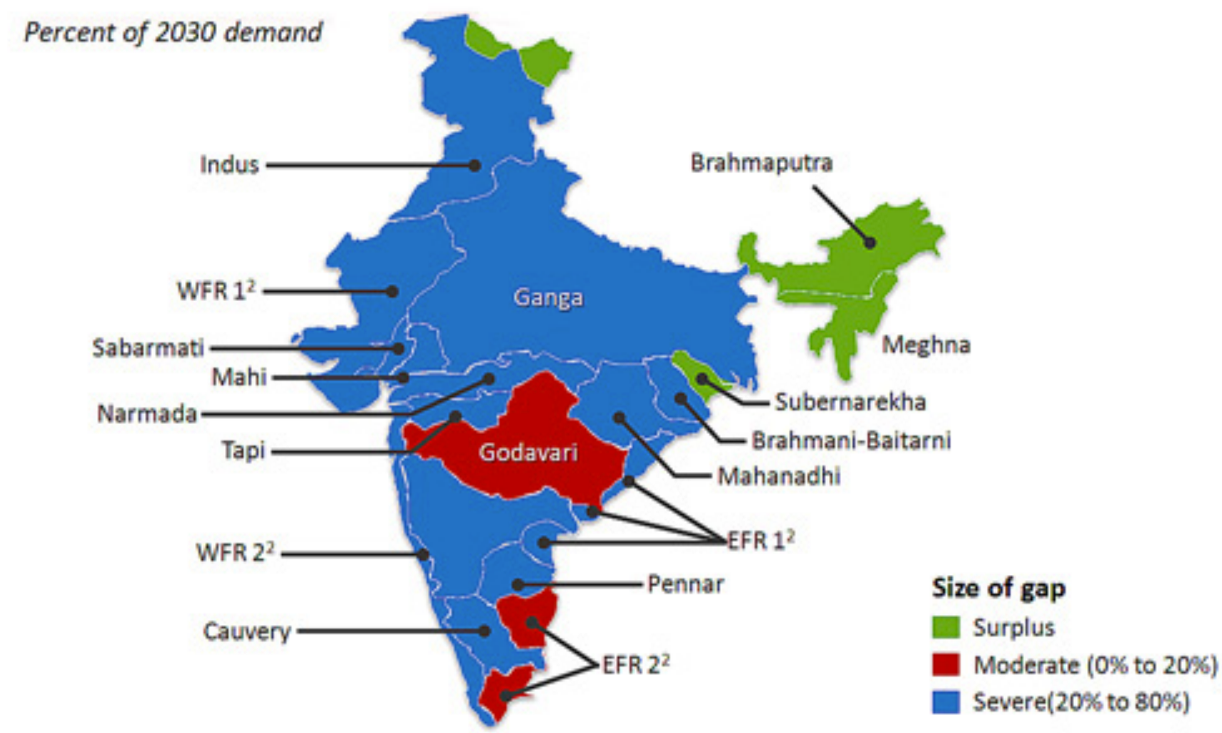

Figure 23 - Most of India is projected to have some gap between the supply and the demand of water in 2030. The blue regions above, which make up the majority of the map, are projected to be the hardest hit, highlighting the need for an increase in supply [85].

Indian Solar Energy:

All of India receives plenty of solar energy, as is confirmed by the map below. Numerically, the majority of Indian states receive greater than the 5 kWh/m^2 global average, making India an attractive place for HDH based on thermal criteria [80].

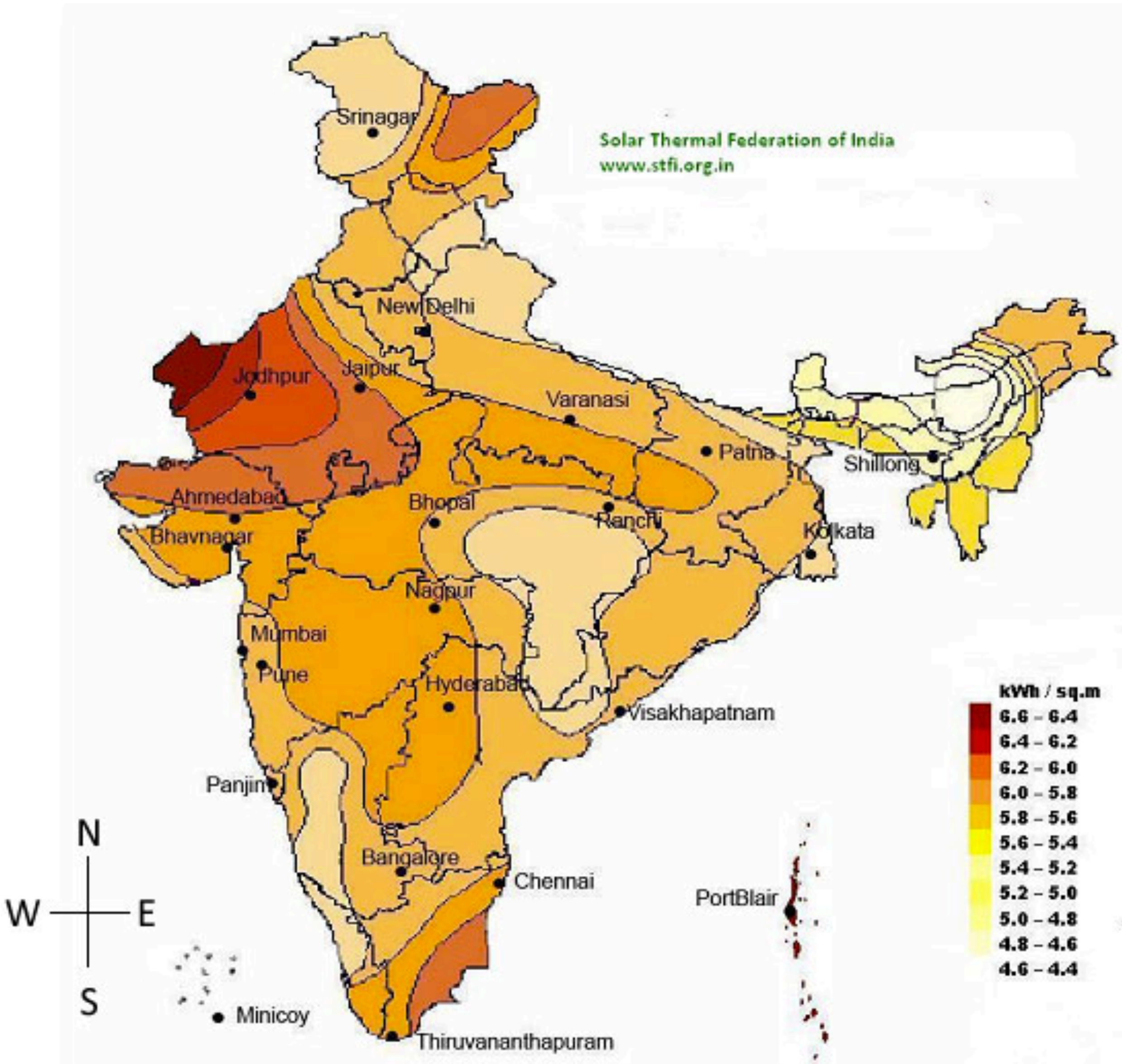

Figure 24- Almost all of India gets above the global average solar radiation. This makes India an attractive place for HDH[14].

Indian Village Density:

In the preliminary analysis of target markets, population density was used as a excluding criteria for the target markets. Population density, however, is a bit of a skewed metric when the implementation plan for HDH is also considered. HDH is most likely implementable in villages, and therefore, more than population density, village density is the important metric of how distribution costs will scale. Regions with a high density of villages (population centers with less than 5000 people: defined by the Indian census) will have reduced distribution and advertising costs, and could even allow for word of mouth marketing to occur between villages. Regions with low village density will be costlier to blanket.

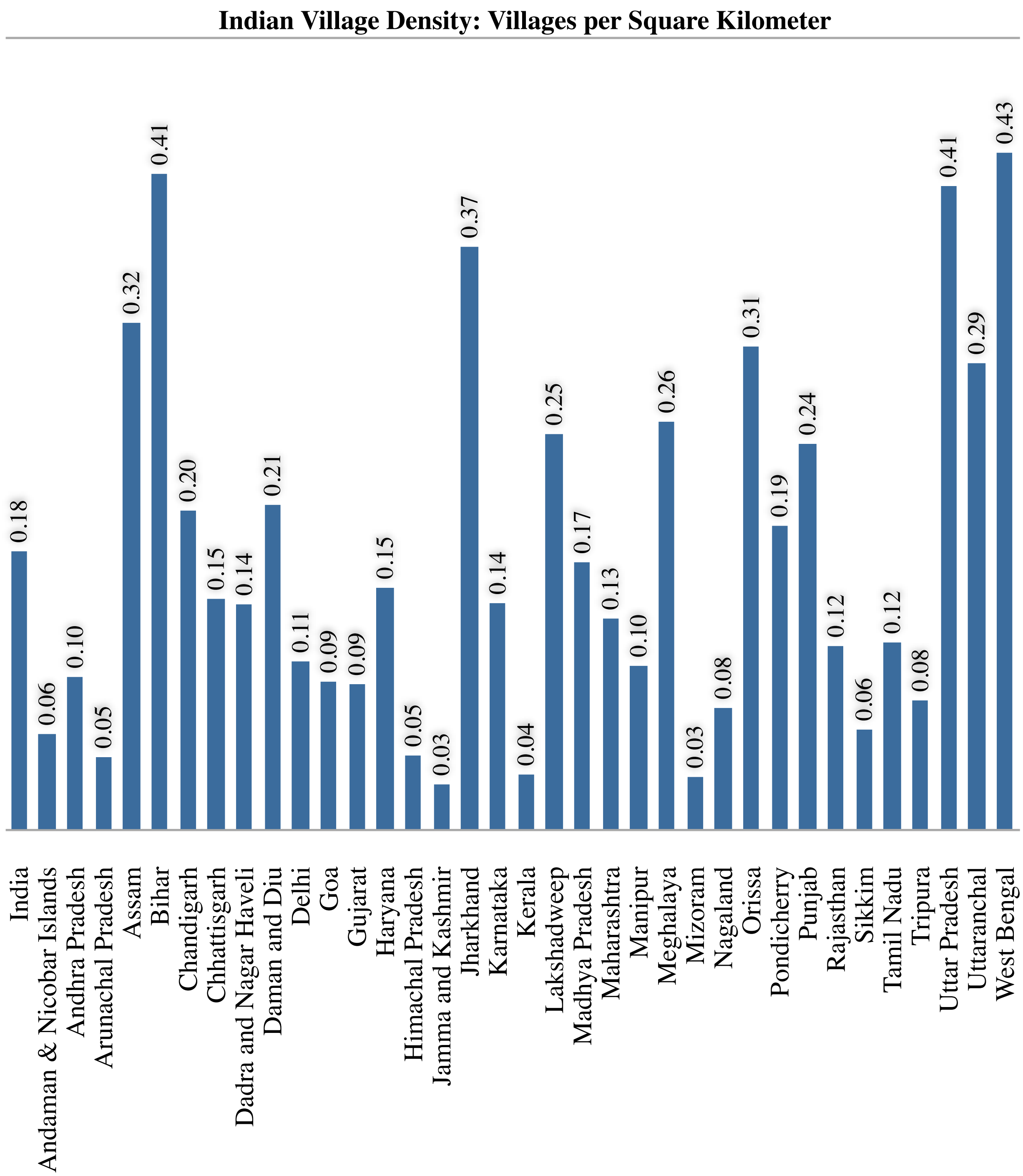

Figure 25 - Indian village density by state [90]. Note that the Indian average is .18 Villages per square kilometer, or about 1 village every 5 square kilometers. Regions which are significantly above this level are highlighted in Figure 26 below.

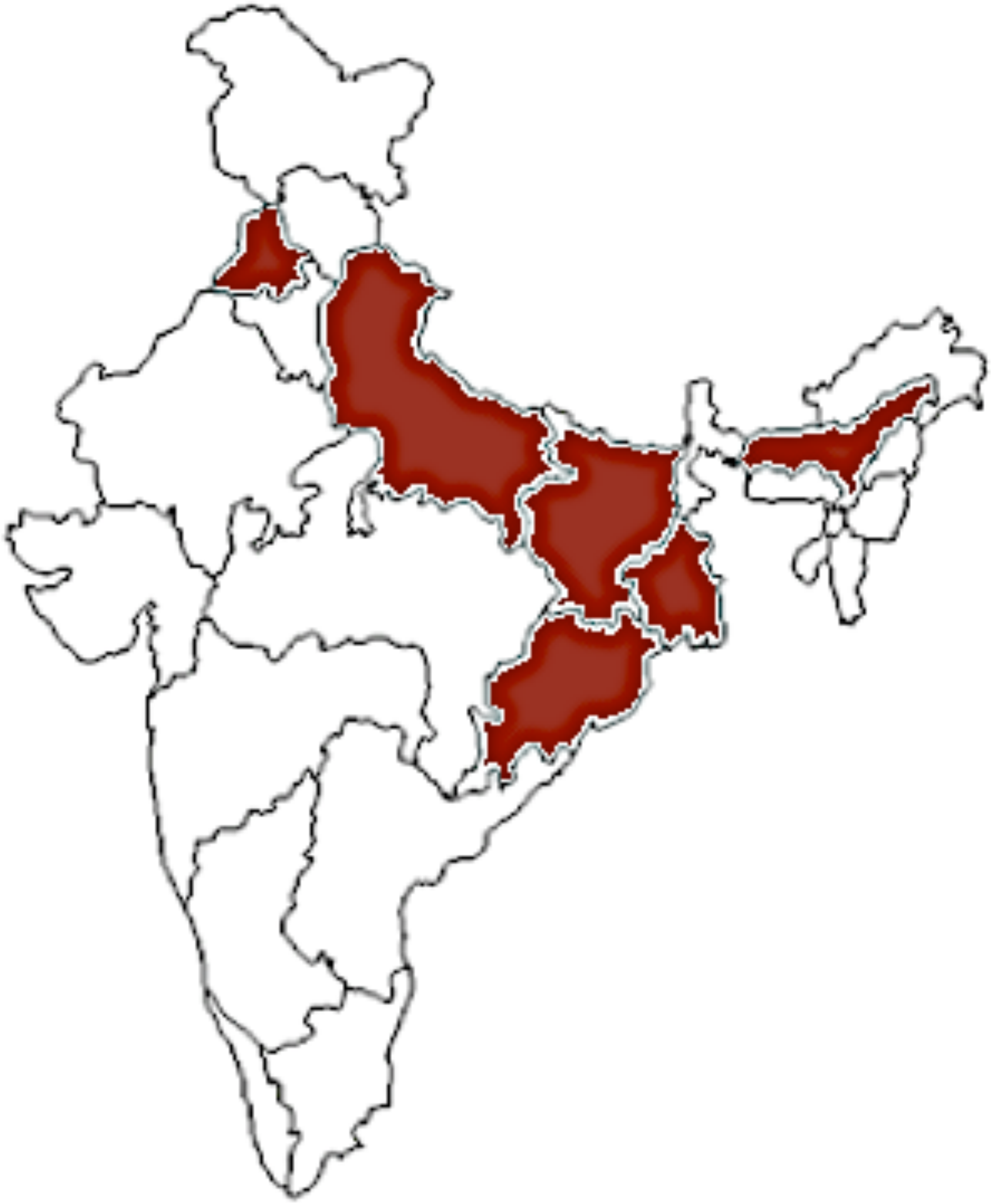

Figure 26 - Areas with village densities significantly greater than the Indian average are shaded in the map of India above. These regions will be set against the other identifying criteria to determine attractive target regions.

Indian Poverty Rates:

Just as for the larger global market, money is still a factor in determining which regions of India need HDH the most. Once again, regions which are financially better off will tend to install reverse osmosis or thermal systems, and will not consider HDH as the primary technology.

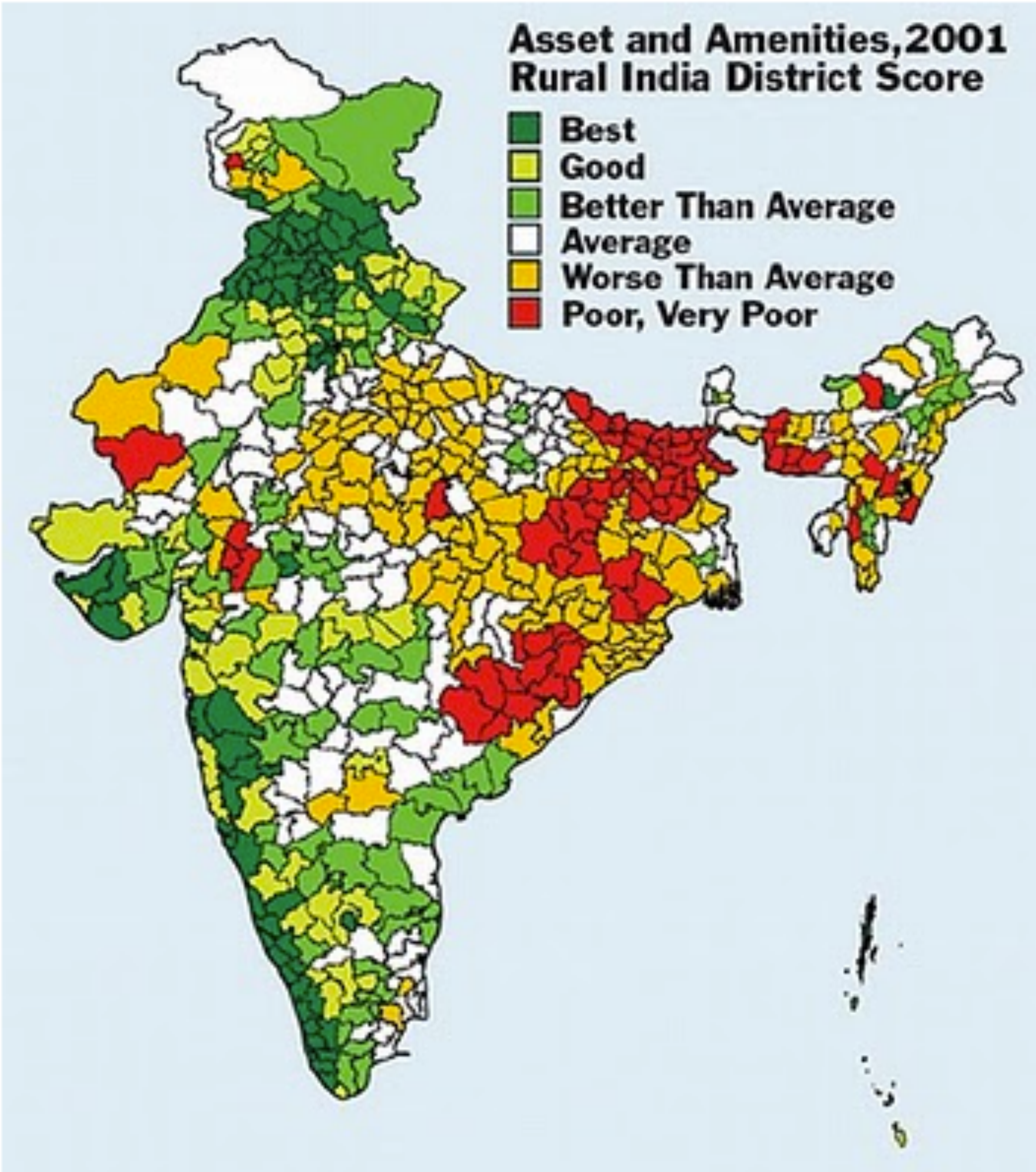

Figure 27 - Poverty rates drawn from the Indian census in 2001 but tabulated by the Naxalite Maoists. The map has been cross checked against the Indian census data to ensure that the tabulation has been done properly. The map displays that the portions of India in orange and red are suffering from levels of poverty greater than the rest of the nation [86].

Indian Electricity Distribution:

Regions which have lower electricity availability will prefer HDH systems. However, the data as it is presented here is not granular enough to provide an image of the village level electricity situation. Data which is specific enough to supply information regarding the electricity situation for specific villages was not found. Therefore, the data here will not be considered, save to say that if better data were to be found, it could be used here for further market elimination.

Figure 28 - Indian electricity production capabilities by state as of 2009. The data is not granular enough to target specific villages, and is therefore not used in the analysis. However, should better data become available on a village level, it should be used here.

Indian Literacy Rates:

Finally, regions with low literacy rates are again targeted because it implies that more complex technologies requiring skilled labor for repair, such as RO, are not as viable in the villages.

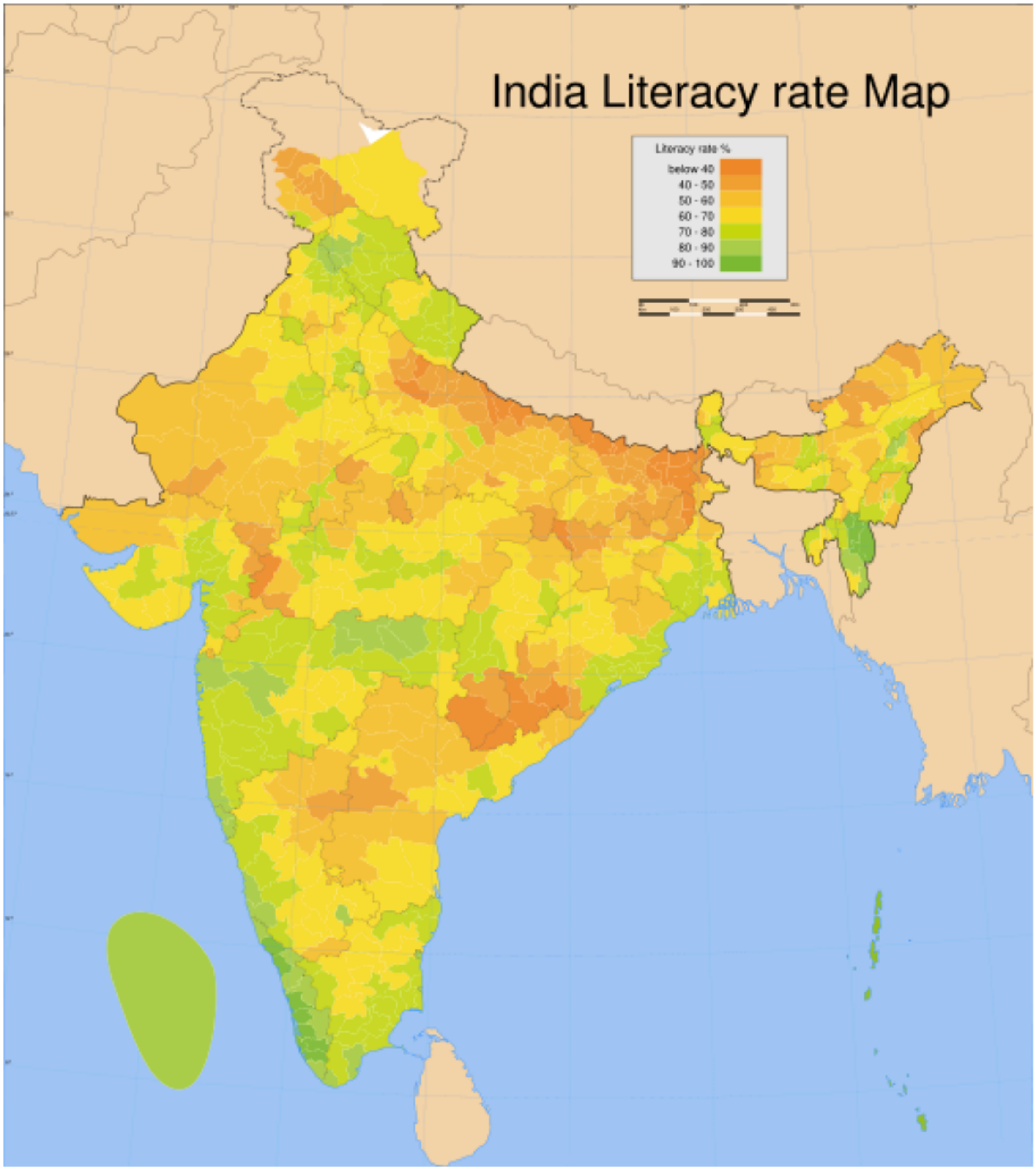

Figure 29 - The yellow and orange areas of the map highlight the areas in India with lower literacy rates. These areas are better targets for HDH implementation for the same reasons described in the larger market analysis above [84].

Target Regions for the Indian Market:

Once again, these maps are compared and the overlay produces the most viable market in India. In this case, the Indian States of West Bengal and Orissa seems to be the most viable. These states have severe water shortages, high solar radiation, high village density near the ocean, are quite poor, and the population is not very well educated (fig. 30).

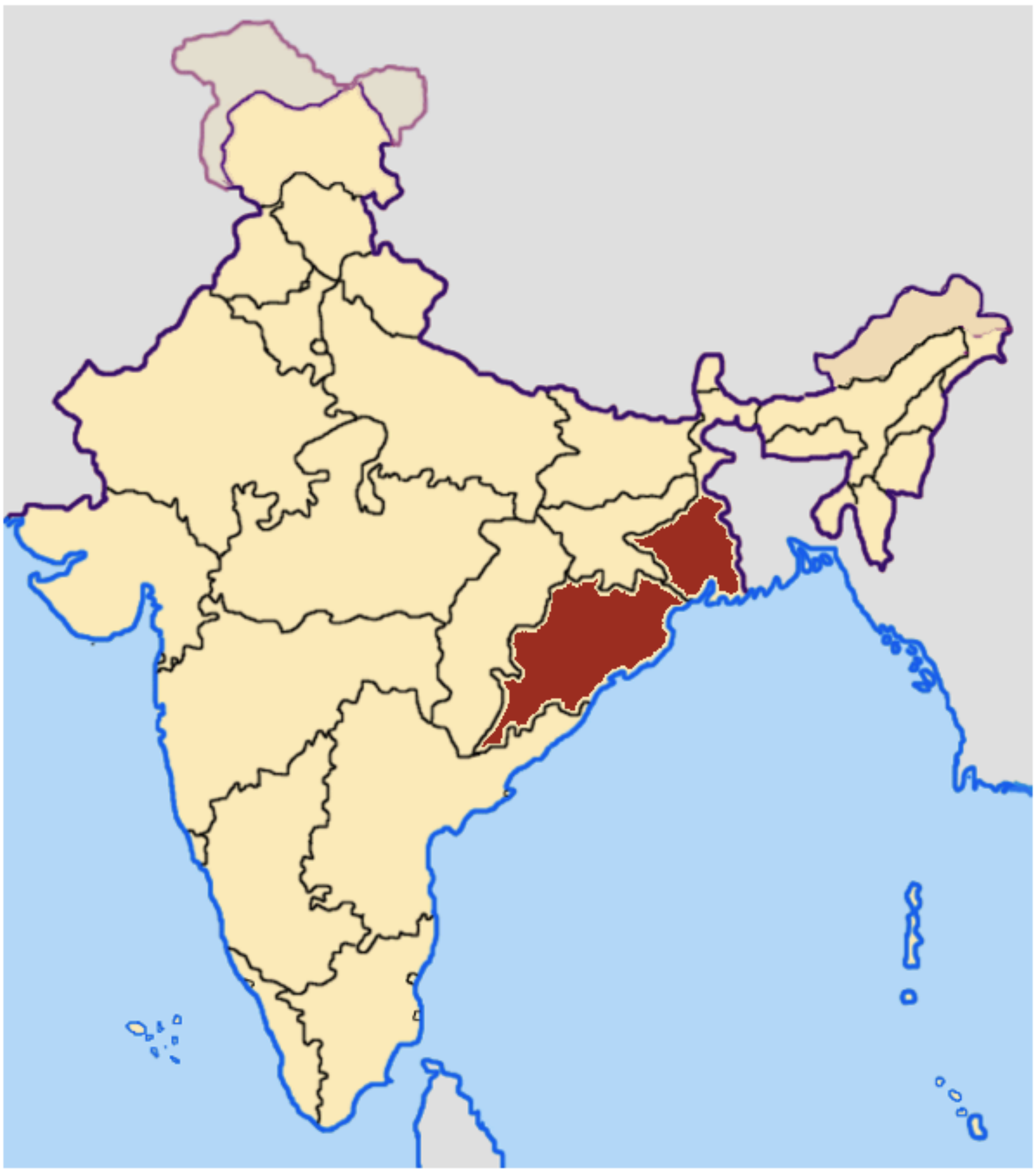

Figure 30 - Through the use of the same criteria applied to the global market, West Bengal and Orissa have been selected as the best candidate for HDH implementation.

Target District:

Even simply narrowing the market to states within India is not complete. By further analyzing the data above, the district of South 24 Parganas in West Begal shows the most promise as a location for initial deployment. South 24 Parganas, highlighted in a zoomed in version of West Bengal, sits right next to the sea and fits

Figure 31 - The district of South 24 Parganas fits every market criteria perfectly. Through the market reduction approach, it has been shown to be the first place in which the HDH system should be implemented.

every other criteria perfectly. The district is one of the largest districts in West Bengal with a total population of 6,909,015. It has a very high density of villages, with an estimated 84% of that population inhabiting rural areas. Moreover, these rural communities lack clean water. While the 16% of the population which lives in the urban centers are afforded the Indian government standard of 250 people per clean water source, the rural regions of the district are closer to 400 people per water source. This lack of clean water sources means women have to travel farther to get the daily water for their families, and that clean water for sanitation is unavailable. The literacy rate is also low, hovering close to 60%, which means more complex technologies are not viable [91]. Therefore, through a complete analysis of the global markets, the district of South 24 Parganas should be targeted for implementation of the HDH system.

4.3 Possible Limitations of the Market Reduction Method

While the market reduction method used did lead to a specific region in West Bengal which proved to be an excellent candidate for further implementation, that does not mean that there are not other regions which are equally viable, or even that South 24 Parganas is necessarily the best region available. One possible source of error is in the varying depth of the data collected and analyzed. Some maps are very specific, going down to a country level globally and a district level in India. Other maps tend to highlight broader swaths of land, and therefore do not provide the same level of detail which would allow more precise market determination. Another source of error is simply in a lack of data present. Ghana and Eastern Africa were omitted from further study because detailed data was not available. Finally, certain assumptions were made in deciding what criteria to apply to the target markets. For example, literacy rates were assumed to connote a general lack of repair capabilities. However, it may be the case that in certain regions literacy and technical training are not necessarily linked, as technical expertise may be passed down through experience rather than texts. Compounded, a change in the data used or the data available, and a change in the criteria used, might have produced a very different result from the one actually garnered.

However, given that the district finally targeted fulfills every constraint set forth, the analysis has proven to be at least somewhat of a success in this case. Presently, an initial implementation plan for penetration of the South 24 Parganas market is set forth.

5. Implementation

Implementation requires the most real world feedback compared to the other sections of Technology and Market. The Technology section, which looked at competing methods of preforming similar tasks, and the Market section, which narrowed the world into target regions, were both fairly research heavy exercises. Implementation, on the other hand, is the only section which really requires immediate feedback to prove and hone in on a workable methodology.

Nevertheless, one potential implementation scheme is outlined below, which has been used by companies already successful in the rural product space.

5.1 Case Studies in Selling to Rural Populations

Clean water is an enabling resource. It provides the drinker with better health, increased energy, and general peace of mind. Moreover, an easily accessible clean water source not only helps to save significant sums of money in terms of avoided medical expenses and sick days, but also frees up time which might have been required for trips to the water source. This saved time and money opens up the possibility of business opportunities which might have otherwise been missed. In this way, clean water is a powerful resource, with the ability to help people increase their overall income and possible begin the climb out of poverty. Clean water, when viewed through this value lens, mirrors many of those products sold by mirco-lending operations around the world. Thus, understanding the methods by which those other products were successfully marketed should provide a model for a successful implementation strategy for HDH.

5.1.1 Grameen Phone

The concept for Grameen Phone (GP) captures this value narrative. The founder, Iqbal Quadir, grew up in rural India. As his family did not have access to medical resources, he once spent an entire day walking over ten miles to get medicine for his brother, only to find that the doctor was not available. Years later, while reflecting on this episode, Quadir realized the potential time which could have been saved if he had only had a phone to call the doctor's office beforehand. The simple thing of access to a phone could have allowed Quadir to preform and benefit from a day's worth of labor rather than wasting time walking to and from this distant doctor's office [87].

This is the essential GP value proposition. By viewing the phone as a time saving, value generating tool, GP is able to use a very clever financial model to enable even the poor to own cell phones. GP first sells the phone to a member of the rural poor at an extremely low cost, in fact, often at a loss. GP then trains this individual to use the phone, and shows them how they can charge others to make calls. Finally, GP collects money from the individual based on the usage of cell phone minutes.

Through this method, Grameen Phone has done several things to increase their odds of successful implementation. They have aligned the value generated for the phone user with the payment scheme. Only when the user makes calls on the phone, hypothetically saving them time and money, does the user split some of that 'savings' with Grameen Phone in the form of payments. They have also enabled individuals in the village, generally women, to act as entrepreneurs, by training them in the usage of the phone, and allowing them to make a profit through sales to the community. This training of village entrepreneurs gives Grameen Phone a much stronger village specific marketing ability, as the chosen village entrepreneur presumably knows the village dynamics and is able to sell better because of her familiarity with the village culture. Moreover, by allowing the entrepreneur to increase her profits by innovating to increase sales, GP has provided a profit motive to the village salesperson. Finally, if the salesperson entrepreneur of the cell phone does not make their payments to GP, Grameen Phone is able to block that cell from using the network, effectively forcing the entrepreneur to either pay their bill, or live without the service. Through this financing model, GP has become the dominant cell provider to the rural poor in Bangladesh, with over 27 million subscribers and almost $900 Million in revenue [88].

While the implementation plan for HDH will not mirror GP exactly, the use of micro-lending to reduce the cost of the system to the customer, and the view that water, just as the phone, is a value generating resource, make the Grameen Phone model relevant to the understanding of rural markets.

5.1.2 Water Health International

Just as a phone, selling clean water should be no different. Water Health International (WHI), a startup company currently operating in 200 villages in India and in 400 villages in other parts of the world, has proven that a similar model to the one used by Grameen Phone can be successful in the water market. WHI provides cheap, UV filtration to kill microorganisms in water, and has a very similar value proposition to HDH technology. Quoting directly from WaterHealth's website:

> *"Benefits of the technology include high efficacy, high throughput, a small footprint, and long-term reliability. The modular design means that systems can be scaled to serve communities of various sizes. Non-proprietary components that are coupled with UVW in WHI's installations are readily available in most parts of the world. Ease-of-use and low maintenance requirements mean that our systems can be deployed even in the most remote locations."*

High efficacy, a small footprint, long-term reliability, ability to scale, and the use of local materials are all common competitive advantages claimed by WHI and the Lienhard group's HDH technology. Moreover, Water Health recently received $15 Million in financing from the International Finance Corporation, whose South Asia director in a statement about financing WHI, noted:

> *"As more villages are added, the project will help generate local employment and provide training, significantly improving earnings of rural households."*

This statement, combined with the success of the WHI business plan, proves that clean water can be treated as an enabling product, whose use and availability can provide a significant monetary boost to the user. WHI's method of capturing this value is essentially the same as that used by Grameen Phone, with a few slight variants.

First, WHI enters a new village by providing financing for a centralized water filtration facility. Essentially, Water Health provides a full loan to build a facility in a village. Then, as the villagers use the water from the facility, they slowly pay back the loan by paying a bit more than the true cost per liter, eventually paying to the point where they have paid off the loan and now own the water source. Throughout this process, water health enlists local villagers to work in the facility, creating local jobs and building up knowledge in the process. After the loan is fully repaid, Water Health encourages the individuals that are now trained in the process to becomes salespeople for other villages, essentially breeding new entrepreneurs. Also, once the facility is paid for, the village itself has the opportunity to sell the water to other communities at a profitable rate.

In addition to providing a loan for the water purification plant, Water Health also partners with local health officials to spread the word about the harms of drinking polluted water. Not only does this truly benefit the villagers by informing them about the adverse affects of drinking polluted water, but it also creates a demand for the clean water which WHI is providing. Essentially, this education provides the backbone to the proposition that water is a good which will provide the villagers with a value greater than the cost of the good itself. This health educational facet is therefore a critical part of the Water Health Plan [89].

Note that the WHI facility is centralized in the village. This ensures that only villagers who continue to pay for the service receive the water. Therefore, just like the case of Grameen Phone, WHI has the security to stop providing service to those who do not pay, allowing the business to act not as a charity, but as an actual for profit company.

One clear difference between the WHI facilities and the HDH system is generating capacity. The WHI system is able to produce upwards of 50,000 L/day, well over 1000 times that of the HDH system. Therefore, the WHI business model must be slightly changed to reduce the dependence on the village for financing, and work on a more family oriented basis. Nevertheless, details of both of these case studies are relevant in determining an overall strategy for the implementation of the Lienhard group's HDH technology.

5.1.3 Targeting Women

Women are the focus of NGO micro-lending around the globe. Both Grameen Phone and Water Health International specifically target women to run their local operations. Women have been shown to be more reliable than men in paying back loans, and are generally considered better connected to the interpersonal dynamics of the village. Technically speaking, women are considered by NGOs as 'change' agents, as they influence the daily lives of the children and the community more than the males. Women are also in touch with the hardships placed on a family which is forced to drink polluted water, as often it is the woman who is tasked with taking care of sick children or elderly parents.

The male figure in the household is typically the breadwinner in rural communities across India and Africa. He receives the money for his labor first, and choses what portion of it to give to the family. In regions where alcohol abuse and drug addiction are common methods of forgetting the pains of poverty, men tend to spend income that could be used more productively on these vices before giving what's left to their spouses. Micro-financing operations have noted that women, on the other hand, are much more careful with money, as they understand the needs of the family, and do not suffer as gravely from these addictions. As such, women have been shown to have a much greater payback ratio for micro-loans than men, and are much more likely to influence the other women of the community to payback their loans as well [63, 64].

Women are also the primary collectors of water (fig. 32), a fact that was noted to be true in our target district of South 24 Parganas. Assuming the water purification system that is set up decreases the time it takes to collect water while simultaneously increasing the purity of the collected material, the system should prove to be a direct and tangible benefit to women around the world, one that they are more likely then men reliably depended upon to pay for.

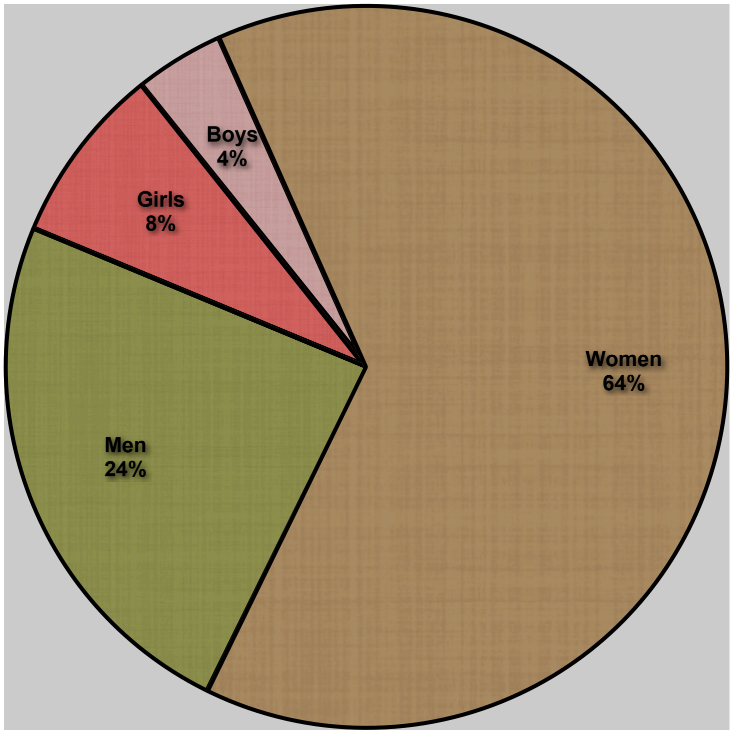

Figure 32 - The percentage of water collection which is done by women, men, girls and boys is broken down above. Women are the primary collectors of water around the globe. Targeting women rather than men is crucial to adoption of the HDH technology worldwide [45].

5.2 HDH Product Deployment Strategy

Given the data from Grameen Phone and Water Health International, along with the general NGO data about women as the smart target for micro-lending, a strategy can be crafted which takes all of this into account but is specific to the HDH system.

5.2.1 End Customers: Rural Populations

As proven by WHI, clean water which can be provided at a low daily cost will save tremendous economic resources and more than justify the price. For South 24 Parganas, and more generally most rural areas, local clean water will decrease rates of illness from waterborne disease, decrease the time spent on collecting water from sparse sources, and enable women by freeing them from their constant struggle for water.

The specifics of a financing plan for the HDH system could manifest as follows. From section 3, the material cost of the facility is about \$12/L. From Table 3, the water production cost is about

$.005/L. Therefore, one individual's drinking water supply of 3L/day will run a one time cost of about $35 plus a daily fee $.015.

In order to make the one time fee of $35 affordable, it can be split over 5 years, and paid off daily whenever water is purchased. If this is done, then the daily cost of the water is only 3.5 cents, or about 2 Indian rupees per person. If water is to be purchased by a family of 4 every day, and a fee of 10 rupees is charged, this would yield a profit of about 2 rupees per family per day to the company.

WHI claims to have about 600 villages currently covered by their water facilities. They also advertise that each facility can supply about 50,000 liters of pure water per day. If this is the case, then their current generating capacity is 30 Million liters per day. If this same capacity were reached by hundreds of thousands of HDH systems, and given a profit of 2 rupees for every 12 liters of water bought, that would yield a daily profit of $100,000 or about $35 Million a year in profits. This is a sizable sum, but is also reasonable considering WHI must generate a similar yearly profit to garner investments of $15 Million. Should the daily cost of 10 rupees proves to be unreasonable for the rural poor, the financing period for the system could be extended beyond 5 years, thereby reducing the price even further.

The generating capacity of the HDH system is much lower than that of the WHI system. The HDH system will likely produce no more than 100L/day, or about 30 people's drinking water supply. This creates multiple challenges. First, a centralized systems which can cut people from getting their water if they do not make their payments becomes more difficult. Secondly, the piping of seawater to each and every system will become much more expensive, possibly to the point where it is impossible to sustain a profitable company given the need for installed piping. Finally, small systems increase the number of systems in circulation, and therefore increase the chance of a single system breaking in some way. This final concern can be addressed by educating the people in the community.

Just as for other NGO's involved in rural areas, women should be the target of any implementation strategy. If a system is designed to provide water for 5 families, the women in those families should be given the loan to purchase the system from the provider, and those same women should be in charge of paying that loan back on a daily basis. The women should also be educated in how to take care of the system, and how to diagnose and repair it should something go wrong. This knowledge should allow the women to care for their systems without the aid of a centralized company, and could also empower the women to work as repair people for the systems of those who do not know how to or care to fix their own systems.

Finally, the implementation plan should tap into respected local officials to spread the word about the dangers of drinking polluted water. This could come in the form of partnerships with local healthcare providers or possibly local religious institutions. Creating an understanding of the health concerns of poor water quality will both help the villagers wellness, but will also create a demand for the desalination system.

5.2.2 Water Suppliers

Piping seawater to local communities is a potential infrastructure hurdle that must be overcome before local desalination efforts can even be attempted. Although seawater is generally a free and available resource, pumping it to the necessary location requires energy and money. South 24 Parganas is a good district for this purpose because it sits next to the sea. However, this proximity to the oceans does not change the need for piping to be installed, even if the water does not have to be pumped over long distances.

As a point of comparison, Water Health International actually installs all of the piping along with its creation of water filtration facilities. Due to their large scale, this model proves to be efficient because they are servicing 500 to 1000 times the people with the same piping costs as a single HDH system would necessitate.

One possible method of getting closer to this scale is to pump water from the sea to a centralized pipe facility in the village, and then to distribute the water to individual systems from there. This would reduce the piping necessary, as pipe does not need to be laid from the sea to each system, but rather only from the central system to each smaller unit. Moreover, a centralized piping center would allow the HDH water provider to cut off the water from those who are not making their payments, enabling one of the critical features of both the Grameen Phone and WHI systems, payment control.

Another possible solution is to simply stack many smaller HDH modules together in a central facility in order to produce larger volumes of water. If using many of the HDH units together proves to be cost effective when compared to producing one large centralized, HDH system, this is a workable solution, with little in terms of technological hurdles. From the price model in section 3.3, the price of an HDH unit will scale up in terms of the defined variable œ. Therefore, if this variable œ is known to be greater than 1 (for example, a doubling of the required generating capacity leads to a tripling of box size), stacking individual, smaller units becomes economically viable. Note that a central facility built up of many smaller HDH modules would solve both the piping and payment control problems.

However, if it proves to be costly to just stack HDH units next to one another, or in other words, if œ is less than one, an HDH system which is capable of producing upwards of 10,000 L/day would be able to essentially replicate the success of the Water Health International implementation model. The 10,000 L/day facility would also be able to institute the village entrepreneur model, the village financial scheme, and would allow for more centralized maintenance.

While the Lienhard group itself has not yet built a system with this generating capacity, systems exist on the market today which demonstrate the ability for HDH systems to scale to these volumes. For example, the TerraWater Desalination System, based in Germany, has been rated to generate 5000 L/day running on solar power. The TerraWater unit uses condenser units which are modularized and put together to form the final unit of a given size [92]. The TerraWater system is a proof of concept for large scale HDH technologies at reasonable costs (approximately $.0015/L production costs), and proves the WHI large generating capacity model is workable even with HDH technology.

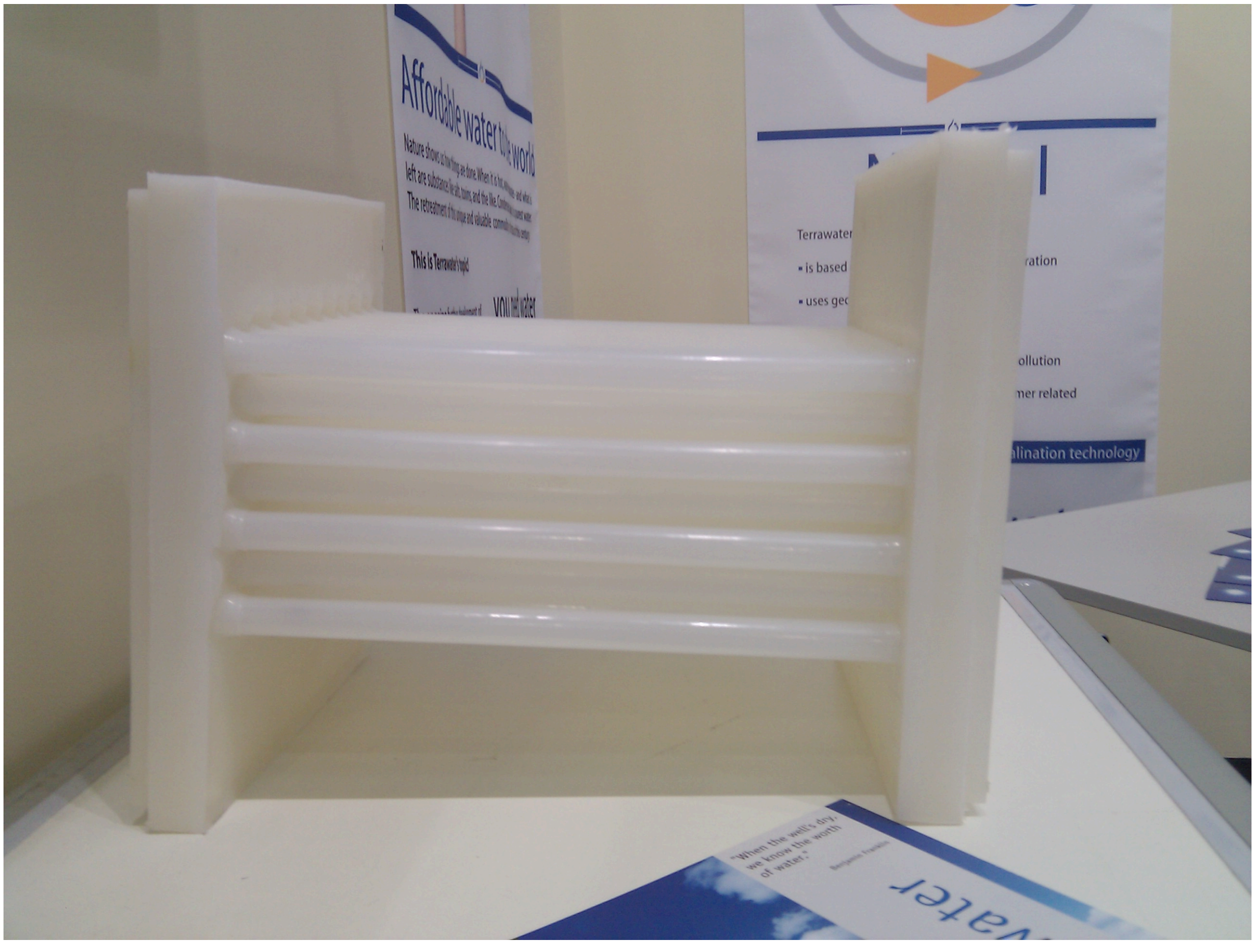

Figure 33 - The TerraWater condenser unit is shown here. The TerraWater system has been demonstrated to desalinate up to 5 m^3/day, which proves that the large scale HDH system is indeed possible. This condenser unit has the ability to stack together with other condenser units in a modular way in order to taylor the generating capacity of each TerraWater system.

6. Recommendation

Providing the rural poor access to clean water is not only a humanitarian necessity, but an economic good. Clean water is an enabling product, in that providing the rural poor with a nearby water source helps to alleviate health concerns and associated costs, and reduces the time spent collecting water. The savings from avoided medical care are obvious, and in a world where time equals money, saved time is just as valuable.

Therefore, it is recommended that a deployment plan for the Lienhard group's optimized HDH technology should take the following action steps:

1) First, at least two model systems, one with cheap parts and one with more expensive parts, should be built here at M.I.T. These systems should be priced, and their relative efficiencies should be measured. This will help to nail down the cost estimates done in section 3.3 and will also provide the group with an idea for unforeseen problems which might be encountered during deployment.

2) Based on the market section of this paper, a village in South 24 Parganas in West Bengal should be chosen to begin implementation. This village should be chosen by doing one final market reduction on the South 24 Parganas district in West Bengal in order to select a specific village. However, the data to do this analysis will most likely come from interactions with local villagers and rural leaders, rather than from academic resources.

3) After a specific village is selected, the size of the job required by the village should be determined based on the number of people who want to use the product in that area. Then, the most cost efficient HDH system should be chosen in accordance with the materials cost analysis in section 3.3. The cost estimates done in section 3.3 should be edited as the cost of local goods becomes better known, and after the relative efficiencies of the cheaper to more expensive units is more reliable.

4) Next, a financial plan should be worked out with the women of the village in order to pay for the system. As villagers are not going to be able to pay the fixed cost of the system upfront, the total cost of the system should be divided over a certain time period (5-10 years), and the daily cost of water should be made to slowly recuperate this investment (villager's don't have lump sums of money at once, but do have money to spend on a daily basis). Part of the financing plan should also try to allow for local employment as a payback mechanism. Employment of the villagers creates buy-in to the process and also trains villagers in system maintenance and distribution.

   The first few systems will require financing which will not see a return for many years. For this reason, the financing for the first few systems will most likely come from internal group sources, rather than from outside investors. Once the business model is proven, outside investment can be secured. Note that outside investment is a must for fast growth of the venture. Using group funds is only viable as a proof of concept strategy.

5) A piping network with a centralized piping facility should be built to the sea. If the systems used in the village are small (1 per household), then piping should lead from the sea to a central piping facility, from which water is distributed. If larger HDH systems can be built centrally in the village, only a single pipe to the main distribution center must be laid, which is of course more cost effective. Either way, the centralized unit should be able to control water flow to villagers, and should shut off water to villagers if payment is not rendered.

6) The villagers should be taught the basic repair necessities of the system. Most likely, the best method of implementing this teaching is through a top down approach. One should begin by educating a few villagers in the skills required to repair the system. Have these villagers make money from repairing broken systems and allow them to teach others their skill. This allows the system to become self sustaining, which frees up the technology to grow into other areas without having to constantly monitor previously established regions.

7) Finally, partnerships should be made with local health officials to teach the villagers about the necessity of clean water, increasing demand for the system while benefiting the villagers health. If these partnerships prove to be expensive, then one can pay the health officials based on the volume of water sold, essentially giving them an incentive to convince more villagers of the need for clean water. This is a demand generating step, and is crucial for complete buy-in from the village.

Throughout each of these steps, the results should be constantly evaluated and used to tweak the methods. Overall, the HDH system still has a ways to go before full commercialization is possible. Hopefully, this thesis has laid down the first step in true deployment of the system. Maybe someday soon, the phrase will be: “Water, water, everywhere, and *enough* drops to drink.”

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